Improvement of EAF efficiency through an integrated control of scrap melting and slag characteristics

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Several innovations have been introduced into the EAF system during the last decades. The improvement of energy efficiency and production rates are probably related to a correct integration of the different systems and to a correct design of the scrap charges as a function of the production rate, of the metal losses and of the energy consumption that are considered an optimal compromise to fulfil a correct economic balance for the melting, decarburation and dephosphoration operation. In order to achieve the aim of an energetic advanced model has been developed through the integration of the energy model of electric and chemical sources with the ones treating the metal bath oxidation and the foaming behaviour of the slags.

KEYWORDS:
steelmaking, melting, Electric Arc Fornace, scrap, slag, fume analysis

INTRODUCTION AND HISTORICAL OVERVIEW

In the last 40 years several technological innovations applied to Electric Arc Furnaces have allowed this kind of plant to become competitive in the production of both special and common carbon steels\(^1,2,3,4\), starting from recycled steel scraps. This strong competitiveness has been reached by the progressive increasing of the installed power which can be erogated by electric current and the exploitation of the combustion processes. Between 1965 and 1970 the need of increasing the production rates implied the introduction of oxygen injection featured by high flow rates, which increased the speed of steel oxidation and allowed the exploitation of the heat related to the presence of carbon combustion and the consequent formation of CO; 1975 saw the first application of the furnace walls cooling system by means of water cooled panels and these devices were introduced for mitigating the increasing thermal stresses on the refractory materials associated to the rising power provided by the arc.

One of the most significant innovations for Electric Arc Furnaces was introduced in 1978: the formation of foamy slags which shield the refractory walls against the radiation of the heating arc. These slags, obtained through carbon enrichment and oxygen injection, reach an average height of 0.3 m, which is about three times the value assumed by non foamy slags. Such a thickness can be reached only by a correct managing in the injection of graphite powder and oxygen and it allows to work with long arc even when the whole scrap charge is melted, because the arc keeps itself submerged and surrounded by the slag, that absorbs most of the thermal radiation causing, a noticeable decrease in the thermal stresses on the walls and on the vault. In 1979 the introduction of wall burners took place, in order to reach two operative aims: the exploitation of the chemical energy developed by the combustion of natural gas (CH\(_4\)) and the heating of the cold spots along the furnace perimeter, related to the geometry of the electrodes. The effort of exploiting the energy coming from the chemical sources has known a strong intensification also during the last twenty years, especially for increasing the savings of electric energy, mainly in the countries featured by a strong dependence on hydro-carbides for the production of electric energy. The latest technical innovation which deserves attention was introduced in 1983 and was represented by the Eccentric Bottom Tapping (EBT), which allowed fast tapping with no slag dragging or with a significant minimization of this phenomenon which can pollute the successive refining steps. All these innovations drove to remarkable improvements in the process features: in 1965 the tap-to-tap time was approximately 3 hours with a specific electric consumption of 630 kWh; nowadays the melting of 95 t of steel requires 35-40 minutes and the needed electric consumption is about half than 40 years ago (around 320 kWh/t\(^5,6,7\)).

In this context the role played by the features of the steel scraps has been usually considered as a secondary aspect, often evaluated on the basis of only empirical relations without the involvement of a systematic approach, so that in a lot of steelmaking unities the classification of the steelscrap is regarded as an important issue only during the commercial negotiation and not for the definition of the charged mixes that can maximize the productivity and even the metal losses during the melting operations. On the basis of such a historical landscape and of the EAF performances, the goal of an increasing performance can be reached through the correct integration of different aspects involved in the melting plant. One of the aspects that can imply a favourable and significant efficiency improvement is associated to the correct scheduling of the energy supplying as a function of the scraps mix and of its change in heat transmission. Several interesting and rigorous studies have been focused on the changes of the physical properties of massive bulk steels\(^8\), that certainly represent the theoretical basis for more complex modelling, but it is not directly suitable for the simulation in the arc furnace system. With the
exception of the electrode automation, the other aspect strictly
associated with the optimization of the power supply can be rea-
ched through a correct evaluation in the use of the scraps and
by a correct controlling of the fume analysis that allows to mo-
nitor the efficiency of the combustion.9,10,11,12 The
integration of these aspects can represent a useful tool for
increasing the efficiency of the melting process in terms of
energy savings and decrease of the metal losses.

ASPECTS INTEGRATED WITHIN THE MODEL
Scrap Classification
Scrap mixes usually melted by means of Electric Arc Furnaces
are made up of different scrap typologies; there is a European
Reference Rule which classifies the different categories on the
basis of their geometric features, paying a particular attention to
the thickness. Moreover, the European Reference also fixes the
maximum percentages of some alloying elements, such as copper
and tin, which can be accepted in the steel scraps.
The scrap classification for the use as raw material for electric
furnaces includes six different typologies, which can be defined
on the basis of their geometric features:
• L (obtained from sheets): thin wastes of maximum thickness
up to 3mm;
• D (obtained from demolition): old scraps characterized by big
thickness (more than 5mm thick), including pipes and hollow
sections of satisfactory thickness;
• T (obtained from turning wastes): homogeneous or mixed bat-
ches of carbon steels or cast irons of known origin, i.e. burrs
from automatic steel processing are excluded from this cate-
gory, due to the high sulphur content.
Scrap mixes usually contain even P (Heavy) and R (Gathered)
materials, both of thickness smaller than 6mm, and PR (for
scrap obtained from proler), made up of homogeneous elements
of small sizes.
A significant attention should be paid to the effective scrap mix
introduced into the furnace, especially if the steel mill has no
control systems monitoring the geometrical features of the char-
ged scrap. This represents a critical aspect, because as a matter
of fact different scrap mixes can give rise to different material
losses at the end of the melting process.
This is clearly understandable in Figure 1, where the results of
a statistical analysis on all the melts carried out in 13 months for
a 150 t EAF steelmaking unity are reported for an overall quan-
tity of 1.45 Mt.
The graph shows the results ordered from the best month (mi-
imum losses) to the worst one (maximum losses) as a function of
the correspondent scrap mixes. Clearly the percentages of
each scrap type are not constant and can vary in a significant
range from one month to the following, but some statements can
be put under evidence: the losses rise with the percentages of L
and T scrap types charged in the EAF. This can be preliminary
explained on the basis of the higher surface/volume ratio featur-
ing the scrap types producing the highest losses: this geometric
feature certainly drives to a higher volume of dirty and pollut-
ant elements dragged into the furnace and to a more severe oxida-
tion, especially in case of long permanence of the scraps in
the stocking zones.

Jet-slag-steel interaction
The study of the interaction among oxygen jet, steel and slag can
be very difficult to be simulated dynamically, but it represents
a fundamental aspect to achieve a better control and more re-
gular practice of the oxygen injection. This aspect has important
consequences on the oxidation of the steel bath, on the heat de-
development after oxidation of the chemical elements contained
in the bath and on the formation of the slags. The efforts per-
formed by different authors have led to significant result using
an approach based on dimensionless numbers to summarize the
interaction among the involved fluids: injected gas, bubbles,
steel and slag.13,14,15,16,17,18 The
problem is too complicated to be treated according the fi-
nite element approach whose performances are detrimentally
affected by the numerical stability, so on the basis of the litera-
ture analysis seems to be more profitable a more stable appro-
ach based on the application of the dimensionless numbers.
The dimensionless number that will be taken into ac-
count19,20,21,22,23,24,25,26,27:
• Reynolds number
It is the ratio between the turbulent force and the viscous one
and it can be used to estimate the features of the jet leaving the
nozzle
\[
\text{Re} = \frac{u_d D}{\nu}
\]
(1)
or to evaluate the gas blowing around the bubbles developed
within the slag
\[
\text{Re} = \frac{D}{\nu}
\]
(2)
• Froude number
Ratio of the inertial forces to gravitational ones and it can be
used to represent lance blowing and possible bottom blowing
\[
Fr = \frac{\rho u^2}{g}
\]
(3)
or it is used to estimate the inertial forces to gravitational ones
produced by the gas jet on the foamed slag:
\[
Fr = \frac{I^2}{g}
\]
(4)
• Capillary number
\[
Ca = \frac{\rho u^2}{\sigma}
\]
(5)
• Weber number
Ratio of momentum intensity to properties of liquid, then it is
used to characterize droplet generation and it involves both jet

FIG. 1  Losses of the charged material as a function of the
scrap categories (experimental data collected
during the industrial trials).
Perdite percentuali del materiale caricato in funzione
della tipologia del rottame (i dati sperimentali sono stati
registrati da operazioni fusorie realizzate con forno
industriale).
momentum and the properties of liquid from which the droplets are ejected

\[
W_e = \frac{\rho L^2}{(\rho R_0 \sigma)^{1.5}}
\]  

(6)

- **Momentum number**

Ratio between the jet momentum and the displaced liquid inertia

\[
M_n = \frac{\rho L^2}{\rho R_0^2}
\]  

(7)

The use of the dimensionless numbers has been applied with success also for the study of the foaming behaviour\(^{28,29,30,31,32,33,34,35,36}\).

The involvement of the formerly presented numbers allows the correct description of slag movement and the reliable interpretation of the slag foaminess as stated by Lotun et al.\(^{36}\). The concept of foaminess has been widely discussed and the conclusion is that it represents an idealization not supported by physical evidences. After the evaluation of several works and the comparison among the recorded experimental data found in literature, it is possible to conclude that the relation among the foam thickness and the average size of formed bubbles is:

\[
H = kCu^a \cdot \frac{\sigma}{\rho} \cdot r^b \cdot \gamma^c
\]  

where \(k=2617\) \(\alpha=-1.01\) \(\beta=-1.74\) \(\gamma=1.77\).

Such a relation has been obtained through the application of the Buckingham Pi-theorem and so it is based on a robust approach.

The obtained relation can be changed in:

\[
H = 2617 \cdot \frac{\rho_a^2 \cdot j_a^2 \cdot \sigma_a}{\rho \cdot \gamma^2 \cdot r^2}
\]  

(9)

substituting the dimensionless number with the involved physical variables.

One of the most interesting conclusions is the role played by the surface tensions which is present at the numerator of the relation (9) and at a first sight this does not appear consistent from a thermodynamic point of view. This is due to the fact that the really significant variable is the ratio \(\sigma/\rho\) and the \(r\) value of the bubbles is strictly dependent on the surface tensions. The higher is the surface tensions the lower is the \(r\) value and so the slag is thicker (Figure 2, Figure 3), so the proposed relation does not contradict the basic thermodynamic principles and it can be applied to improve the performance of the simulation trial to be applied.

The consistency of the obtained results suggests that the proposed relation can be a useful tool for developing the model related to the slag-bath interaction in order to grant a more regular process.

The maximization of the foaminess improves the protection of the refractory walls that are shielded by the heat irradiated by the electric arc.

**Oxidation and decarburization of the steel bath**

Assumed that the refining period – of an EAF – is the time starting from the complete melting of the metallic charge until tapping, during this period the steel inside the furnace may be considered a liquid phase.

The injection of oxygen in the bath produces two main effects: the oxidation of the elements in solution with the steel, and the generation of heat that contributes to consequent electrical energy savings. Both these phenomena have to be described by a single model, since they are closely related.

The energy developed by the oxidation is valuable by the reaction enthalpy, once the number of reacting moles are known.

![FIG. 2 Relation between \(\sigma/\rho\) and the bubble radius.](image)

*Relazione tra il rapporto \(\sigma/\rho\) ed il raggio della bolla.*

![FIG. 3 Relation between surface tension and bubble radius.](image)

*Relazione tra tensione superficiale e raggio della bolla.*

Then the problem is to choose the chemical species oxidized in the bath and the calculation of the number of moles of a certain chemical species in solution that are oxidized by oxygen during a fixed time range.

The first point can be solved through the use of oxygen potentials.

Considering an oxidation reaction:

\[
\rho \text{met} + O_2 \rightarrow f(\text{oxides})
\]  

(10)

According to Wagner theory the oxygen potential for this reaction is:

\[
\Delta \mu_{O_2} = \Delta \mu_{O_2}^0 - \rhoRT \ln(a_{\text{oxide}}) + fRT \ln(a_{\text{oxides}})
\]  

(11)

To quantify the moles reacting, kinetics of the bath must be taken into account.

The diffusion laws give the number of the moles for a certain species that can move to the interface surface with the jet in \(\Delta t\). In terms of concentrations \(C\):
where the transport constant $\beta_i$ for each species can be calculated in turbulent conditions as:

$$\beta_i = \frac{1}{2}D_i^2\nu_i^2\sigma_i^{-1}$$  \hspace{1cm} (13)

Since the difference between the diffusion constants for the elements dissolved in the steel bath are not significant for the description of the treated industrial case, only a single value for $D_j$ has been used for all the species to simplify the computation:

$$D_j = 0.5 \times 10^{-6} \text{[m}^2\text{s}^{-1}]$$  \hspace{1cm} (14)

The velocity $u_i$ is the average value of the steel velocity in correspondence of the cavity generated by the $O_2$ flow inside the bath. The velocity of steel can be calculated applying the momentum transfer between jet and bath:

$$\nu_{steel}(x) = \sqrt{\frac{\rho_s}{\rho_o}} \nu_o(x)$$  \hspace{1cm} (15)

and $u_o$ is the average value over the range covered by the jet inside the bath:

$$u_o = \frac{1}{\tau} \int_{0}^{\tau} \nu_o(x) \text{d}x$$  \hspace{1cm} (16)

The carbon injection and its integration in the model.

In the common melt shop practise and in the observed heats during the refining period of the melting operation, the carbon injection in the slag takes place too. This is needed for some main reasons: first of all to avoid an excessive oxidation of the slag, to increase scrap yield and to promote the formation of foamy slag.

The role played by the carbon injection in the decarburisation phenomena has been studied in the same way operated for the oxygen injection through the use of kinetic factors $\xi$ (each one different for each component of the slag)(Table 1):

$$\Delta E_i = \xi \Delta H_i$$  \hspace{1cm} (17)

and with the introduction of carbon potentials (analogous to the oxygen ones) for the reduction reactions in the slag:

$$\frac{1}{n} \left(\text{Me}_nO_{2n}\right) + C \rightarrow \frac{2}{n} \left[\text{Me}\right] + CO$$  \hspace{1cm} (18)

The reactions of SiO$_2$ and Al$_2$O$_3$ were neglected because their reduction potential is too high in the EF process.

If there is oxygen left from the oxidation of the first elements, this oxygen can react with the elements with higher potentials. Only the free moles of oxygen left by each oxidation can react with the elements with higher potentials.

The amount of each species coming to the surface can be estimated. If there is oxygen left from the oxidation of the first element featured by the lowest oxygen potential it becomes available for the oxidation of the next lower element in the oxygen potential scales and so on.

On every time interval the activities of the elements at the surface can be evaluated considering the moles consumed in the former step by the oxidation reactions and the diffusion laws. The temperature is evaluated at every time step by adding the heat developed by each reaction. The temperature difference in steel is true under the adiabatic hypothesis for the reaction surface:

$$\Delta E_j = \Delta H_j \left[ m(i) - m(t + \Delta t) \right]$$  \hspace{1cm} (20)

The enthalpy can be evaluated by:

$$\Delta H_j = \Delta H^0_j + c_p \left( T - T_{298.15} \right)$$  \hspace{1cm} (21)

where $\Delta H^0_j$ is the value of enthalpy at standard conditions for the $j$ reaction and $c_p$ is the specific heat at constant pressure. They can be easily evaluated according to Barin Knacke data (Table 1).

The sequence of this computation is developed for each time step taken into account to follow the thermo-chemical evolution of the considered system.

The decarburisation process can be limited by the flow of oxygen and by the carbon diffusion. When the oxygen consumes all the carbon available on the reaction surface and can oxidize elements with higher potential, decarburisation is limited by the carbon diffusion to the interface. On the other hand, the carbon consumption is controlled by the oxygen flow.

The application of the model in the condition of the observed industrial process show that this transition takes place in the range of 0.2-0.4% (weight) of carbon in the bath. This matches the data presented in the bibliography about this topic. The same can be observed for the other elements considered in the model. The described approach has been used to evaluate the chemical energy produced during the affination of the steel bath ($P_{affin}$).

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\Delta H^0_j$ (kJ/molO$_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4/3 \text{Al} + O_2 \rightarrow 2/3 \text{Al}_2O_3$</td>
<td>-1088</td>
</tr>
<tr>
<td>$\text{Si} + O_2 \rightarrow \text{SiO}_2$</td>
<td>-882</td>
</tr>
<tr>
<td>$\text{C} + O_2 \rightarrow \text{CO}_2$</td>
<td>-366</td>
</tr>
<tr>
<td>$2\text{C} + O_2 \rightarrow 2\text{CO}$</td>
<td>-198</td>
</tr>
<tr>
<td>$2\text{CO} + O_2 \rightarrow 2\text{CO}_2$</td>
<td>-533</td>
</tr>
<tr>
<td>$1/2 \text{CH}_4 + O_2 \rightarrow 1/2 \text{CO}_2 + \text{H}_2\text{O}$</td>
<td>-372</td>
</tr>
<tr>
<td>$2/3 \text{CH}_4 + O_2 \rightarrow 2/3 \text{CO}_2 + 4/3 \text{H}_2\text{O}$</td>
<td>-319</td>
</tr>
<tr>
<td>$2\text{Fe} + O_2 \rightarrow 2\text{FeO}$</td>
<td>-508</td>
</tr>
</tbody>
</table>

**TAB. 1 Enthalpies associated to the considered oxidation reactions.**

*Entalpie associate alle reazioni di ossidazione considerate.*

**Analysis of the off-gas**

The analysis of the off-gas has been performed as a function of the formation of the foaming slag, the oxygen flow rate and the one of the methane. For the optimization of the process the me-
thane flow rate, the oxygen flow rate and the ratios CO/CO$_2$, CO$_2$/O$_2$-tot, CO$_2$/O$_2$-inj have been taken into account. The increase of CO$_2$ fraction has to be reached in order to improve the energy efficiency, while an increase of CO flow rate points out a loss of the chemical energy that can be exploited. A poor CO flow rate can suggest the possibility to increase the oxygen introduction avoiding the iron oxidation.

ANALYSIS OF THE MONITORED HEATS
The experimental activity has been performed in order to realize a correct validation of the model. 1200 heats have been analysed. The analysis has been made easier by the subdivision in 3 groups as a function of the consumption of the electric specific energy:
- Low Level: 310÷355 kWh/t (Figure 4);
- Middle Level: 355÷400 kWh/t (Figure 5);
- High Level: 400÷440 kWh/t (Figure 6).

The increase of the CO$_2$ and the decrease of CO at the end of each EAF treatment is always associated to an increase of the oxygen flow rate (Figure 7, Figure 8, Figure 9). Moreover, the increase of the electric energy consumption is always associated to an unstable working of the oxygen-methane burners. The electric distorsion is particularly evident at the beginnig of the melting step of the scrap after its charging.

An excessive fraction of CO in the EAF atmosphere is not desirable for the loss of the enthalpy developed by the complete oxidation to form CO$_2$ that cannot be exploited for melting. The increase of the carbon injection seems to be strongly related with a significant increase of the electric energy consumption (Figure 10).

The most reliable hypothesis is that the added graphite powder could heat the slag but there is not any significant contribution to the increase of the bath thermal level and consuming a fraction of the introduced oxygen that is no longer available for enthalpy development that promotes the melting of the charged scrap.

MODEL
The treated aspects can be difficult to be integrated in a single model and the possible application of those results in a single tool can be difficult, especially if the automation system needs to be robust and fast.

The obtained results can be summarized in a unique model based on the energy balance.
the input data of the model are the different action times ($t_x$), $P_{\text{elec}}$, the enthalpy reaction data associated to the oxidation reactions, the final temperature of the bath and the initial temperature, while $t_{\text{tot}}$ is the tap to tap overall time and it can be isolated and computed in order to evaluate the melting and the decarburization EAF period. Because of the heat conductivity varies as the melting goes, an incremental time procedure is needed to take into account the progressive variation of the physical ruling variables. These variables are involved in the computation through the variation of the efficiency in heat transfer ($\eta_x$) that has been estimated through the experimental measurement. Thus, the equation takes another form:

$$
\sum \eta_x' \frac{\Delta E}{\Delta t} = P_{\text{elec}} - \frac{\Delta E}{\Delta t} + n_{\text{tot}} \eta_{\text{tot}} f_x
$$

(22)

The value of $P_{\text{elec}}$ varies as a function of the energy provided to the steel bath and on the heat loss ($H_{\text{loss}}$) imposed by the operational conditions. This relation can be considered at a specific instant (i) since the beginning step:

$$
\sum \eta_x' \frac{\Delta E}{\Delta t} = P_{\text{elec}} - \frac{\Delta E}{\Delta t} + n_{\text{tot}} \eta_{\text{tot}} f_x
$$

(23)

The efficiency associated to each energy term is a function of the internal energy supplied to the steel bath and the possible heat losses (especially the ones related to heat dispersion from the walls, the fumes and the slag mass to be maintained at the correct thermal levels):

$$
H_{\text{loss}} = M_{\text{steel}} (f_x' - f_x) + \eta_{\text{tot}} f_x
$$

(24)

The value of $P_{\text{elec}}$ varies as a function of the energy provided to the steel bath and on the heat loss ($H_{\text{loss}}$) imposed by the operational conditions. This relation can be considered at a specific instant (i) since the beginning step:

$$
\sum \eta_x' \frac{\Delta E}{\Delta t} = P_{\text{elec}} - \frac{\Delta E}{\Delta t} + n_{\text{tot}} \eta_{\text{tot}} f_x
$$

(25)

The efficiency associated to each energy term is a function of the internal energy supplied to the steel bath and the possible heat losses (especially the ones related to heat dispersion from the walls, the fumes and the slag mass to be maintained at the correct thermal levels):
The losses of the developed heat is partially included in the efficiency heat transfer coefficient ($\eta_h$), but the heat dispersion through the refractory walls and the water cooled modules have to be taken into account. In the terms $P_{\text{heat,1}}$ and $P_{\text{heat,2}}$ all the combustion reactions have to be taken into account and these include also the combustion due to the carbon injection to promote and maintain the foaming slag (2nd paragraph).

\[ H_{\text{loss}} = H_{\text{loss,1}} + H_{\text{loss,2}} + \Delta T_{\text{loss}} \left( T_{\text{inlet}} - T_{\text{outlet}} \right) + H_{\text{loss,grav}} \left( T_{\text{inlet}} - T_{\text{outlet}} \right) \]

The terms involved in the loss term are related to the heat needed to maintain the slag hot (inserted CaO and formed slag), heat transfer through the slag, heating of the refractory walls and the heat absorbed by the water cooled panel, where $\Delta T_{\text{loss}}$ represents the measured difference in the thermal temperature between the inlet section and the outlet one. The last term is associated to heat loss due to the opening of the furnace for the charge of the different baskets. This last term should be divided in the discretized elements.

DISCUSSION AND CONCLUSIONS

The energy model has shown a good agreement with the experimental data. It is interesting the role played by the flow rate of the water cooled panels and the one covered by the graphite powder injection needed for forming and maintaining the foamed slag. It is interesting that some terms can have certainly favourable defect, but also possible drawbacks.

- the oxidation of iron and alloying elements produces also an amount of slags that have to be maintained at the correct thermal level although the low heat conductivity and the high specific heat of the oxide compounds;
- although the carbon injection introduced to permit the formation of foaming slag represents a consolidated practice, this action has to be reasonably contained. Actually, the implementation of the developed incremental energy model has pointed out a carbon oxidation whose enthalpy is not efficiently transferred to the steel bath and related protection of the oxidation of iron and alloying elements that react in a lower fraction. This phenomenon is evident also in the fume analysis and in the evaluation of the electric energy in presence of an excessive presence of graphite addition;
- the described situation suggests that the useful and favourable formation of a foamed slag featured by significant height should be promoted by also alternative method, i.e. gas introduction and bubble formation from the bottom of the EAF furnace. Actually, a good a highly foamed slag (350-450mm) can perform a favourable insulating effect that has been taken into account in the decreasing of $H_{\text{loss}}$.

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Abstract

Miglioramento delle prestazioni del forno elettrico ad arco mediante un controllo integrato del tipo di rottame e delle caratteristiche della scoria

Parole chiave: produzione di acciaio, forno elettrico ad arco, rottame, scoria, analisi dei fumi

Diverse innovazioni sono state introdotte nei forni ad elettrico durante gli ultimi decenni. L’incremento dell’efficienza energetica e dei tassi produttivi sono stati gli obiettivi che hanno guidato questa evoluzione. Un’ulteriore incremento dell’efficienza dei sistemi fusori si svelerà probabilmente legato ad una corretta integrazione degli aspetti relativi alla tipologia del rottame caricato, alla cor...
La modulazione dell’energia elettrica e chimica e alla stabilizzazione delle scorie schiumose. Le perdite di massa metallica caricata risultano strettamente correlate con la morfologia e tipologia del rottame (Fig. 1), mentre la stabilizzazione della scoria schiumosa può essere correttamente studiata attraverso l’utilizzo del teorema di Buckingham (Figg. 2, 3). Un modello energetico è stato sviluppato per rendere conto delle variazioni del consumo specifico di energia elettrica al variare delle condizioni di esercizio (Figg. 4, 5, 6) a cui corrispondono diversi andamenti dei fenomeni di ossidazione e di sviluppo delle specie chimiche ad essi associati (Figg. 7, 8, 9). Le rilevazioni sperimentali ed il modello matematico confermano che l’introduzione eccessiva di polverino grafite sviluppa per rendere conto delle variazioni del consumo specifico di energia elettrica al variare delle condizioni di esercizio (Figg. 10).

**List of symbols**

- \( a \): Activity
- \( \Delta \): Enthalpy at standard conditions [J/mol]
- \( h_{steel} \): Vertical depth in the bath calculated at a certain ascissa [m]
- \( H \): Enthalpy [J/mol⁻¹]
- \( H_{loss} \): Overall loss of the enthalpy [J]
- \( H_{open} \): Enthalpy lost during the furnace opening [J]
- \( He \): Height of the exit transversal section of the nozzle above the plane level of the bath [m]
- \( \Delta F \): Enthalpy at standard conditions [J/mol⁻¹]
- \( j \): Reduced surface gas velocity (m/s)
- \( Re \): Reynolds number
- \( u_g \): Gas velocity at the outlet section of the nozzle (m/s)
- \( u_s \): Gas velocity of the gas jet (m/s)
- \( u_r \): Average velocity of steel in correspondence of the jet surface (m/s)
- \( \mu_g \): Viscosity of the gas phase (Pas)
- \( \mu \): Viscosity (Pas)
- \( \xi_i \): Proportional kinetic constant for oxide \( i \) slag [s⁻¹]
- \( \varepsilon_i \): Concentration of moles of the specie \( i \) [mol/m³]
- \( r \): Average radius of the bubble contained in the foam (m)
- \( \rho \): Density (kg/m³)
- \( p_G \): Density of the gas phase (kg/m³)
- \( p_s \): Density of the liquid phase (kg/m³)
- \( \rho_0 \): Jet density [kg/m³]
- \( \rho_{apparent} \): Apparent density of the charged scrap [kg/m³]
- \( p_m \): Density of the injected gas at the entry transversal section of the nozzle [kg/m³]
- \( \sigma \): Surface tension (Nm)
- \( x \): Depth of cavity (m)
- \( We \): Weber number
- \( \Delta \mu_{O_2} \): Oxygen standard potential [kJ/mol]
- \( \Delta \mu_{O_2} \): Oxygen potential [kJ/mol]
- \( \Delta T_{water} \): Temperature difference of the water between the inlet section outlet one of the cooling system [K]
- \( \Delta t \): Time interval [s]
- \( k_{slag foamed/unfoamed} \): Slag conductivity in foaming or non foaming condition [W/mK]
- \( L_p \): Latent heat melting [272kJ/kg]
- \( m(t) \): Moles of the oxidized species at the time (t) [mol]
- \( M_{melted} \): Mass of the refractory [kg]
- \( M_{slag} \): Mass of the formed slag [kg]
- \( \rho_{steel} \): Density of the liquid steel [kg/m³]
- \( \rho_{water} \): Temperature difference of the water between the inlet section outlet one of the cooling system [K]
- \( \rho_{ref} \): Temperature of the refractories at time step (n) [K]
- \( \rho_{ref} \): Density of the refractories at time step (n) [m³]
- \( \Delta \mu_{O_2} \): Temperature of the steel after (n) discretized step [kJ/mol]
- \( \Delta \mu_{O_2} \): Average velocity of the steel[m/s]
- \( V_{inlet} \): Velocity of the oxygen jet[m/s]
- \( V_{ax} \): Axial velocity (component of the velocity along the axis of symmetry of the jet) [m/s]
- \( \alpha \): Axial coordinate taken from the nozzle outlet [m]
- \( \beta \): Abscissa where the axial velocity is zero [m]
- \( \gamma \): Abscissa of the intersection of the jet axis with the plane of the bath surface [m]
- \( \omega \): Stoichiometric coefficients
Ottimizzazione pratiche operative in un forno elettrico ad arco (iCSMelt®)

P. Frittella, A. Lucarelli, B. Poizot, M. Legrand

Il tool “iCSMelt® - intelligent Care Steel Melting”, è stato sviluppato dal Centro Sviluppo Materiali (CSM) con lo scopo di ottenere pratiche operative ottimizzate (OOP – Optimized Operating Practices) per la gestione del processo di fusione nel Forno Elettrico ad Arco (FEA) una volta definita la funzione obiettivo di interesse (OF - Objective Functions), come ad esempio Power on, costo della colata, consumo di energia.

L’articolo presenta i risultati dell’applicazione di iCSMelt® presso l’impianto FEA DC di Duferco La Louviere (DLL) nel progetto “Control and optimisation of scrap charging strategies and melting operations to increase steel recycling ratio - CONOPT-SCRAP” condotto con il contributo finanziario del fondo di ricerca per il carbone e l’acciaio della Comunità Europea (Research Fund for Coal and Steel).

INTRODUZIONE
Oggi giorno la necessità di ridurre il consumo di energia (e conseguentemente delle emissioni specifiche di CO2), parallelamente all’aumento di produttività, rimane ancora il principale obiettivo per la produzione di acciaio da ciclo elettrico. Recentemente si propongono R&S che industrializzano il monitoraggio/ controllo delle diverse fasi del processo FEA attraverso l’integrazione di:

- sensori HW, disponibili al momento (analisi composizione fumi, misura temperatura del bagno liquido, valutazione altezza della scoria ecc.) [1-3];
- sensori SW per ottenere informazioni non direttamente disponibili tramite misurazioni (es. modelli metallurgici per composizione e temperature di acciaio e scoria) [4-6];

Consequentemente HW e SW sono potenzialmente disponibili per sistemi di controllo processo di nuova generazione mirati a minimizzare l’impiego di energia elettrica e chimica e raggiungere la composizione chimica e la temperatura di punta mento dell’acciaio [7-9].

Inoltre l’incremento del prezzo del rottame ha spinto i produttori di acciaio ad usare rottami di minor qualità o sostituiti del rottame (HBI, DRI) al fine di contenere i costi. Dunque l’attenzione deve essere posta sulla affidabilità e flessibilità del processo FEA e sulla ripetibilità delle prestazioni in termini di temperatura e di tap to tap, consumo di energia (sia chimica che elettrica), composizione e temperatura dell’acciaio liquido allo spilloaggio. Questo richiede di superare le pratiche attuali, guardando all’inserimento nel processo di produzione dell’acciaio, dal caricamento del rottame sino alla fase finale del processo di affinazione, considerando l’interdipendenza tra le singole fasi del processo (figura 1).

Una strategia globale di controllo del FEA (figura 2) è il primo passo della integrazione tra i controlli di FEA e dell’affinazione in LF. Diversi sviluppi sono attualmente in corso [10-12]. Questo articolo riguarda un primo tassello di tale strategia ottenuto attraverso l'accompagnamento tra bilancio di massa e di energia con un ottimizzatore (giallo in figura 2), in un tool chiamato “intelligent Care Steel Melting - iCSMelt®” e la sua applicazione al FEA DC di Duferco La Louviere S.A dove il sistema è stato customizzato e applicato nell’ambito del progetto RFCS “CONOPT-SCRAP”.

DESCRIZIONE iCSMelt®
Il sistema “intelligent Care Steel Melting iCSMelt®” è stato sviluppato con lo scopo di ottenere Pratiche Operative Ottimizzate (OOP), partendo da Pratiche Operative Standard (SOP) in uso presso un FEA secondo le Funzioni Obiettivo (OF) selezionate. L’iCSMelt® include diversi moduli (figura 3):

- iCSMelt® Process Model (iCSMelt-PM), il simulatore di processo;
- iCSMelt® Calibrator (iCSMelt-Cal) il sistema, basato sulla metodologia degli Algoritmi Generici (GAs), per la taratura automatica dei parametri di calibrazione di iCSMelt®-PM;
- iCSMelt® Optimizer (iCSMelt®-Opt), l’ottimizzatore basato su metodologia GAs.

Tutti i moduli di iCSMelt® (figura 3) sono stati sviluppati in ambiente Matlab® ed opportunamente collegati ad un’interfaccia grafica sviluppata in ambiente .Net.

**PAROLE CHIAVE:**

forno elettrico ad arco, modellistica di processo, pratiche operative, ottimizzazione, algoritmi genetici.
Per quanto riguarda l’applicazione realizzata presso lo stabilimento Duferco - La Louviere, i moduli iCSMelt® sono stati integrati con un sistema di acquisizione dati (DAS) direttamente interfacciato con il primo livello dell’automazione mediante un Server OPC Appli-com®, i dati raccolti vengono memorizzati in un database dedicato. La base dati generata è resa fruibile ai moduli iCSMelt® mediante uno stadio di postprocessing: iCSMelt®-PDA in grado di visualizzare i dati di impianto e di generare gli input per il Process Model. L’iCSMelt® può essere quindi definito un software on site.

iCSMelt® Process Model (iCSMelt®-PM)

iCSMelt®-PM può essere classificato come un bilancio di massa e di energia pseudodinamico. Ogni colata è rappresentata mediante due ceste, ciascuna suddivisa rispettivamente in 4 e 6 fasi (figura 4). Il termine delle fasi è definito attraverso una soglia prefissata per alcuni parametri di processo, o dalla loro combinazione, secondo le esigenze e le indicazioni del produttore di acciaio [13]. Ogni fase è suddivisa in passi temporali (Δt) per ciascuno dei quali viene calcolato il bilancio di massa e di energia (figura 5). I termini presi in considerazione sono:

- materiali in input e relative energie (in bianco): caricamento cesta, aggiunte in forno, piede liquido dalla colata precedente.
- output di processo (in verde): acciaio, scoria, fumi.
- termini della SOP gestiti/scambiati tra iCSMelt®-PM e iCSMelt®-Opt (in rosso): tensione elettrica, corrente, flusso totale di metano, flusso totale di ossigeno, flusso totale di carbone.
- termini indesiderati o controllati in input ed output dal processo (ciano).

I risultati forniti dalla simulazione di iCSMelt®-PM sono:

- acciaio allo spillaggio: temperatura, composizione, peso;
- scoria allo spillaggio: temperatura, composizione, peso, indice di basicità (IB);
- Fumi: temperatura, portata, composizione al quarto foro e nel condotto fumi dopo PC;
- Consumi: energia elettrica (kWh), metano (Nm³), ossigeno (Nm³), carbone (kg);
- Energia: energie in ingresso (elettrica, metano, ossidazioni, post combustione) e energie in uscita (perdite dai fumi e dal raffreddamento acqua dei pannelli e del fondo);
- Durata di ogni fase.
Le diverse opzioni disponibili in iCSMelt®-PM sono:

1. “Da dati d’impianto”: iCSMelt® lavora usando SOP acquisite da DAS e convertite da iCSMelt®-PDA in input leggibili per iCSMelt®-PM.
2. “Da strategia di modellazione”: la simulazione della colata è realizzata seguendo le SOP definite dall’ingegnere di processo; due strategie di conclusione delle fasi sono possibili:
   - “Strategia Tecnologica”: termine fasi in accordo con fasi tecnologiche come in figura 4;
   - “Strategia da Operatore”: termine fasi definito da livelli di consumo specifico di energia elettrica.
3. “Termine simulazione”: definisce la condizione di fine simulazione secondo le modalità:
   - “Alla temperatura di spillaggio”: la simulazione termina alla temperatura obiettiva definita per l’acciaio;
   - “A completamento dei dati”: la simulazione termina alla fine delle SOP definite.

La modalità “Termine simulazione/a completamento dei dati” è usata durante la procedura di calibrazione quando i valori dei parametri del modello sono scelti per raggiungere la temperatura di spillaggio obiettivo nel tempo della colata considerata, mentre “Termine simulazione/Alla temperatura di spillaggio” è usata durante la procedura di ottimizzazione quando è necessario valutare la durata della colata al fine di raggiungere le temperature di spillaggio obiettivo.

iCSMelt-Calibrator (iCSMelt®-Cal)
I parametri di calibrazione sono disponibili nel simulatore di processo, iCSMelt®-PM, per raggiungere il migliore accordo della simulazione con i risultati della colata considerata. E’ possibile effettuare una calibrazione manuale, tuttavia la procedura preferibile è una calibrazione automatica che, in caso di rilevanti cambiamenti nella gestione del processo o nei materiali di carica utilizzati, consentono di trattare un maggior numero di dati di calibrazione in un tempo limitato attraverso i dati disponibili in DAS. I principali parametri usati per la calibrazione di iCSMelt®-PM (parametri di calibrazione) sono:
- ossigeno iniettato coinvolto nella ossidazione del carbonio (K_Oxy_C)
- efficienza dell’ossigeno iniettato nel bagno da lance (K_O_Inj)
- post-combustione nel forno (K_PC_Free)
- ossigeno proveniente dalla porta di scorifica nel bagno (K_Slag_Door)

FIG. 5  Bilancio di massa ed energia per iCSMelt®. Mass and energy balance for iCSMelt®.
- scambio di calore tra rottame nel forno e aria dalla porta di scorifica (P_Factor)
- scambio di calore tra bagno e pannelli raffreddati ad acqua (K_Eq_Tub)

I dati del FEA di DLL in termini di:
- temperatura di spillaggio
- % C nell’acciaio liquido

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**ICS Melt Optimizer (iCSMelt®-Opt)**

iCSMelt®-Opt è basato sul metodo GAs [14-15], la sua funzione è quella di determinare la migliore combinazione dei termini della pratica operativa (OP) al fine di ottenere una colata con il valore ottimale della funzione obiettivo selezionata secondo le richieste e la strategia indicata dall’ingegnere di processo.

Le funzioni obiettivo selezionabili (variabili $y_i$) sono:
- Power on;
- Costo totale specifico;
- Consumo specifico dell’elettrodo;
- Consumo specifico del carbone iniettato;
- Consumo specifico dell’energia totale;
- Consumo specifico di energia elettrica.

I termini della Pratica Operativa gestita da iCSMelt®-Opt sono:
1. intensità della corrente elettrica;
2. portata totale di metano;
3. portata totale di ossigeno;
4. portata totale di carbone iniettato;
5. tensione di TAP.

L’ottimizzazione viene realizzata con un processo iterativo in cui all’avvio iCSMelt®-Opt riceve come input (figura 6):
- indicazione delle fasi da ottimizzare (Phase Optimized Selection);
- intervallo di variabilità dei parametri della SOP per ogni fase (SOP Constrains);
- parametri matematici di gestione del metodo GAs (GAs Management Parameters);
- valori da raggiungere per specifici obiettivi di interesse (heat aims);

ad ogni iterazione iCSMelt®-Opt invia a iCSMelt®-PM la OP posta e riceve da questo i risultati della colata simulata con la OP in oggetto sulla base dei quali iCSMelt®-Opt calcola il risultato globale in termini di una target function espressa come di seguito:

$$ T = \sum \left[ \left( y_i - y_i^* \right)^2 \right] - w_i \sum y_i $$

(Eq.1)

In cui:
- $T$ è il valore della target function;
- $y_i$ sono gli output principali della simulazione della colata (ottenuti con iCSMelt®-PM) per funzioni obiettivo e composizione dell’acciaio liquido [Fe, C, Si, Cr, Mn];
- $y_i^*$ sono valori desiderati (n) per le funzioni obiettivo da ottenere come output del modello (heat aims);
- $w_i$ sono i pesi assegnati ai singoli output del modello fissati come funzioni obiettivo.

Se il valore della target function non soddisfa l’obiettivo indicato il sub-modulo “GAs practices generator” calcola una nuova OP per ottenere risultati migliori rispetto a quella simulata in precedenza.

Il dominio dei valori accettabili per i termini della OP, definito dall’ingegnere di processo, è stato implementato come una estensione del calcolo delle target functions: se il “GAs practices generator” definisce una nuova OP che contiene variabili fuori dai limiti accettabili, l’output del modello è forzato a valori molto elevati (equazione 2):

$$ V = \begin{cases} u_k & \text{se } u_k \in V \\ \infty & \text{altrimenti} \end{cases} $$

(Eq.2)

dove:
- $V$ è il dominio dei valori validi per la pratica operativa;
- $u_k$ è ciascuno degli m componenti specifici della OP.

L’ottimizzazione termina quando la convergenza o il limite di tempo imposto per la procedura sono raggiunti essendo l’obiettivo dell’ottimizzatore quello di cercare una soluzione buona in un tempo ragionevole. Il controllo degli algoritmi genetici è incluso nel “GAs practices generator”, due parametri, configurabili dall’utente, ne permettono la gestione: 1) dimensione della popolazione 2) numero delle generazioni.

**IMPLEMENTAZIONE DELL’ ICSMELT® A DUFERCO LA LOUVIERE**

Le caratteristiche principali del FEA di DLL sono riportate in tabella 1.
Per l’implementazione di iCSMelt® a DLL si possono considerare cinque step che corrispondono ai 5 moduli principali (figura 7) necessari per istallazione, customizzazione e uso.

**Step 1 Acquisizione:** Il sistema iCSMelt® in DLL è stato integrato per scambio dati con il livello 1 (L1) di automazione. I segnali del processo FEA corrispondenti ai dati principali delle colate vengono registrati in un database, DAS, che può essere letto dal Process Data Analyzer (iCSMelt®-PDA) e quindi trasferiti all’iCSMelt®.

**Step 2 Calibrazione:** Sono stati definiti per il FEA di DLL i parametri di calibrazione di iCSMelt®-PM necessari per ottenere lo scostamento minimo dai risultati delle colate. Sono stati considerati per i fumi dei valori tipici, non essendo disponibili delle misure dirette presso DLL, e tre differenti mix di carica tipicamente usati, chiamati menu 30, 47 e 70. I parametri di calibrazione sono stati definiti per gruppi omogenei di colate. La figura 8 riporta, a titolo di esempio, la variabilità del parametro di calibrazione $K_{O_1}\text{Inj}$ per il mix di carica 70. È stata inoltre realizzata una analisi di sensibilità circa l’effetto dei diversi parametri di calibrazione sui risultati delle simulazioni e ne è emerso un forte scostamento della temperatura di spilloaggio misurata per effetto della difficoltà di definizione del parametro $K_{Eq_Tub}$ correlato alle perdite energetiche dai pannelli raffreddati. A seguito di ciò un miglioramento del calcolo della temperatura di spilloaggio, è stato ottenuto attraverso l’introduzione delle perdite energetiche dai pannelli di raffreddamento come input della simulazione, ottenute dal sistema di acquisizione dati e dall’iCSMelt®-PDA.

**Step 3 Simulazione:** simulazione della colata mediante iCSMelt®-PM. Questa fase richiede input generali quali i dati sulla configurazione d’impianto, i diversi tipi di rottame in uso (da inserire nel database disponibile) e la descrizione della suddivisione in fasi oltre che i valori dei singoli parametri impostati a descrizione della SOP. I criteri per i passaggi di fase sono stati adattati alle pratiche operative in uso presso DLL. In figura 9 è riportato, come esempio, il bilancio energetico per il menu di carica 70 in cui:
- L’energia elettrica è il 55 % del totale dell’energia in input mentre l’energia chimica è il 45 %.
- L’energia fornita al bagno acciaio/scoria è il 68 % del totale mentre il 32 % sono le perdite energetiche.

**Step 4 Definizione di pratiche operative migliorate (IOP):** in

**FIG. 7**
Schema generale dell’iCSMelt®, General Scheme of iCSMelt®, configuration.

---

**TAB. 1 Caratteristiche principali dell’impianto FEA di DLL.**
Main characteristics of DLL EAF.

<table>
<thead>
<tr>
<th>General Data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace type</td>
<td>EBT - DC</td>
</tr>
<tr>
<td>Tapped steel</td>
<td>ton 90</td>
</tr>
<tr>
<td>Liquid steel capacity</td>
<td>ton 110</td>
</tr>
<tr>
<td>Shell diameter</td>
<td>m 6800</td>
</tr>
<tr>
<td>Electrode diameter</td>
<td>mm 711</td>
</tr>
<tr>
<td>Transformer</td>
<td>MVA 99</td>
</tr>
<tr>
<td>Max power</td>
<td>MW 80</td>
</tr>
<tr>
<td>Tapping temperature</td>
<td>°C 1620</td>
</tr>
<tr>
<td>Carbon content at tapping</td>
<td>% 0,05</td>
</tr>
<tr>
<td>Number of buckets</td>
<td>2</td>
</tr>
<tr>
<td>Average scrap yield</td>
<td>% 93</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Charges</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Scraps</td>
<td>% 90</td>
</tr>
<tr>
<td>Pig Iron</td>
<td>% 10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operation Data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Scraps buckets</td>
<td>N° 2</td>
</tr>
<tr>
<td>Charge weight</td>
<td>ton 96/98</td>
</tr>
<tr>
<td>Heat size</td>
<td>ton 89/91</td>
</tr>
<tr>
<td>Yield</td>
<td>% 93</td>
</tr>
<tr>
<td>Active power</td>
<td>MW 61 (ave.)</td>
</tr>
<tr>
<td>Power on</td>
<td>min 30/32</td>
</tr>
<tr>
<td>Power off (no delays)</td>
<td>min 10/12</td>
</tr>
<tr>
<td>Tap to tap (no delays)</td>
<td>min 40/44</td>
</tr>
<tr>
<td>Electrical Energy</td>
<td>kWh/ton 360-380</td>
</tr>
<tr>
<td>Electrode consumption</td>
<td>kg/ton 1,1-1,2</td>
</tr>
<tr>
<td>Total Oxygen</td>
<td>Nm³/ton 43-45</td>
</tr>
<tr>
<td>Total gas natural</td>
<td>Nm³/ton 5-6</td>
</tr>
<tr>
<td>Total carbon</td>
<td>kg/ton 30</td>
</tr>
<tr>
<td>Productivity max.</td>
<td>ton/hour 130/140</td>
</tr>
</tbody>
</table>
La IOP 2 (figura 11, tabella 2) è stata inoltre definita con lo scopo di ottenere una riduzione del consumo specifico di ossigeno del 2.5% rispetto alla SOP. Come risultato della colata la IOP 2 prevede una riduzione del 9.97% del consumo specifico di carbone e dell'1.73% del consumo specifico di ossigeno, senza variazioni significative del consumo specifico di energia elettrica.

La IOP 3 (figura 11, tabella 2) è stata invece definita con lo scopo di ottenere una riduzione del consumo specifico di energia elettrica per rispondere ad uno scenario di riduzione della produzione. Per questo motivo l’incremento del tempo di power on è considerato accettabile in un range del 5%. La simulazione iCSMelt® mostra una riduzione del consumo specifico di energia elettrica (-3.1%) e, come atteso, un incremento del tempo di power-on (+3.2%).

TEST INDUSTRIALI DELL’iCSMelt®
PRESSO DUFEERCOLA LOUVIERE
Test con la IOP3
Partendo dal consumo totalsi ossigeno, metano e carbone calcolati da iCSMelt® per la IOP 3, i set per ciascuno degli iniettori sono stati modificati secondo le indicazioni di DLL. Il confronto dei dati delle colate con SOP e delle colate realizzate con la IOP 3 (tabella 3) mostra una riduzione del 3.24% del consumo specifico di carbone e del 2.5% della portata di ossigeno rispetto alla SOP.

Come risultato delle simulazioni effettuate con modifiche delle SOP per il test case IOP2, la simulazione della IOP 2 prevede una riduzione del 9.97% del consumo specifico di carbone e dell’1.73% del consumo specifico di ossigeno, senza variazioni significative del consumo specifico di energia elettrica.
Impianti e processi

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TAB. 2
Visione schematica del confronto tra IOP3 ed SOP simulate tramite iCSMelt®.
Schematic view of comparison between simulation of IOP3 and SOP by iCSMelt®.

TAB. 3
Confronto tra risultati delle colate realizzate con la SOP e con la IOP3.
Comparison between heat data with SOP and IOP3.

La colata 56293 realizzata con la “OOP47 modificata” ha realizzato una riduzione del consumo specifico della energia totale di 0.7%
Tab. 4 Confronto tra SOP, OOP47 e “OOP47 modificata” simolute ed i risultati della colata realizzata con la “OOP47 modificata.”

Comparison between SOP, OOP, “OOP47 modified” simulated and heat result.

Abstract

EAF operating practice optimization (iCSMelt®)

KEYWORDS:
Electrical Arc Furnace, process modelling, operating practices, optimization, genetic algorithms.

The “iCSMelt®” - Intelligent Care Steel Melting” tool, developed by Centro Sviluppo Materiali (CSM) with the aim to obtain EAF Optimized Operating Practices (OOP) in terms of selected Objective Functions (OF), such as power-on, heat cost, energy consumptions, has been customised for DC EAF of Duferco La Louviere (DLL). This paper presents results of the application of iCSMelt® in the frame of the project “Control and optimisation of scrap charging strategies and melting operations to increase steel recycling ratio - CONOPT-SCRAP” carried out with a financial grant from the Research Fund for Coal and Steel of the European Community.

After the modification of the iCSMelt® for Duferco La Louviere EAF calibration of the tool has been performed for reference charge mix. The tool has been used in a first step to manually define new operating practices (IOP). Then iCSMelt® optimizer has been applied to automatically generate optimized operating practices for different charge mixes and different objective functions: minimization of specific consumption of total energy, minimization of specific total cost of the heat, minimization of specific total coal consumption. The industrial application of IOP and OOP, as defined with the support of iCSMelt®, allowed to reach the targets defined by Duferco La Louviere process engineer also if operating practices adjustment was necessary to adapt OOP to the EAF constrains.
One bucket charging Fastarc™ in Jacksonville

D. Patrizio, M. Orsini

This paper describes the main features of the AC Fastarc™ EAF supplied by Danieli to the Gerdau Ameristeel plant in Jacksonville (Florida - U.S.A.). The new state-of-the-art UHP Fastarc™ EAF has a rated capacity of 95 sht (= 86 t) and is capable to handle a single bucket practice, with 100% scrap charging practice.

Thanks to the extended utilization of chemical energy, by means of DANARC™ injection system with Modules technology, and proper sizing of EAF transformer (90 + 12% MVA) the furnace has achieved very fast scrap melting, with promising consumptions figures. The EAF has already achieved Pon time in the range of 35 min, with maximum productivity up to 115 t/h: this results has been achieved thanks to proper oxygen carbon and lime injection, which has allowed to keep good foaming slag condition during all process and lead to fast scarp melting and liquid steel heating up. Moreover the promising performance has been confirmed by the fumes analysis, which has demonstrated the high post-combustion degree inside the EAF.

The homogeneous thermal condition of the liquid bath has been clearly proven by limited steel temperature drops between EAF and caster arrival, in spite of process line without ladle furnace upstream the caster. This paper shows the very interesting results in terms of thermal efficiency and consumptions, based on the data collected in the last months of EAF operation, and the innovative design applied in process, mechanical and electrical parts of the EAF.

KEYWORDS:
Electric arc furnace, melt shop, thermal efficiency, Fast Arc, single bucket

INTRODUCTION
In the beginning of electric arc furnace utilization the melting of scrap was performed by using only arc radiation as energy source. In the last decades instead, the importance of chemical energy has been becoming very high and now its correct utilization is a fundamental aspect in order to produce steel fast and with low costs. In matter of this, the plant of Jacksonville can be considered a representative example thanks to the excellent results achieved in terms of process time, electrical consumption and thermal efficiency of chemical energy. The correct utilization of oxygen, coal and lime injection has allowed increasing oxygen efficiency and exploiting post-combustion reaction of CO in the fumes as much as possible.

EAF FEATURES
The EAF works by keeping a hot heel of 20 t and is designed for a rated tapped size of 95 sht (86 t). The one bucket charging practice has been chosen in order to minimize the power off time. In order to achieve a productivity of about 116 t/h, the expected Tap to Tap time is 44.5 min.

Jacksonville's EAF is shown in Figure 1, whereas the main geometrical data of the furnace are reported in Table 1.

The furnace feeds directly the continuous caster and all ferroalloys additions are made during the tapping phase. The steel is tapped at higher temperature (1700 °C) than usual, in order to guarantee the correct superheat value at caster arrival, without the refining stage in the ladle furnace. Moreover the carbon content at tapping is higher than 0.15 %, which allows limiting the tapping additions thus reducing the relative costs.

TABLE 1

<table>
<thead>
<tr>
<th>Lower Shell Diameter [m]</th>
<th>6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Volume [m³]</td>
<td>130</td>
</tr>
<tr>
<td>Pitch Circle [mm]</td>
<td>1250</td>
</tr>
<tr>
<td>Electrodes Diameter [mm]</td>
<td>610</td>
</tr>
</tbody>
</table>

Electrical Part
The AC EAF is supplied by a HV line characterized by a frequency of 60 Hz and a rated voltage of 230 kV which is turned into 34.5 kV (MV line voltage) by the step down transformer. In the MV line an off-load series reactor is installed in order to increase the cir-
cuit reactance. The EAF transformer has a rated apparent power of 90 + 12% MVA and allows selecting 15 different tap positions to choose the best combination of arc tension, arc current and power factor during the various process stages. The furnace’s secondary circuit is designed for a maximum current of 65 kA.

Specific Power
For Jacksonville’s EAF, a very high specific power has been chosen: 77-78 MW as maximum power. Being the average tapped weight equal to 87.3 t, the obtained specific power is around 0.9 MW/t which is a very high value in comparison to other existing EAFs. Current’s values next to the maximum limit of 65 kA are handled without risks for the electrical plant; moreover the good foaming slag layer allows transferring this energy to the bath and protects wall and roof panels.

FastArc™ Injection Technology
On Jacksonville’s EAF, the “Modules System” has been conceived with four types of injectors, each one with its own specific function, in order to achieve the best possible performance. Figure 2 shows the installed injectors. In case of Lime and Carbonjets a pilot flame is maintained during the injection period in order to protect the material flow and supply oxygen for post-combustion by setting oxygen to natural gas ratio greater than stoichiometric. Oxygenjets 1 and 3 and the Hijet are installed in copper bulged panels.
panels (Figure 3) which allow getting modules close to the bath by protecting them from scrap collapse and ensuring easier bath penetration of oxygen. Figure 4 shows the layout of the modules in the EAF.

Carbon and Limejets are distributed around all the surface of the bath to produce a homogeneous foaming slag layer above the steel level. Oxygenjets also are uniformly distributed in order to insure homogeneous oxygen supply and bath decarburisation. The flowrates and the power at which the modules are used are reported in Tabella 2.

**PROCESS DESCRIPTION**

**Charging Material**

The main products of the Jacksonville plant are billets for rebar and wire rod. The charge mix for the two cases is reported in Table 3. Figure 5 shows examples of scrap charged in the EAF. The scrap density is 750 – 850 kg/m³ due to the large use of shredded (produced inside the plant itself), cast iron and pig

---

**TAB. 2**

*Modules’ features.*

*Caratteristiche dei moduli.*

<table>
<thead>
<tr>
<th>Module</th>
<th>Oxygen flowrate [Nm³/h]</th>
<th>Material flowrate [kg/min]</th>
<th>Max Burner Power [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygenjet 1</td>
<td>2250</td>
<td>-</td>
<td>3.5</td>
</tr>
<tr>
<td>Oxygenjet 2-3</td>
<td>1930</td>
<td>-</td>
<td>3.5</td>
</tr>
<tr>
<td>Hijet</td>
<td>1930</td>
<td>15 – 30</td>
<td>3.5</td>
</tr>
<tr>
<td>Carbonjet 1-2</td>
<td>-</td>
<td>15 – 30</td>
<td>3.5</td>
</tr>
<tr>
<td>Limejet</td>
<td>-</td>
<td>110</td>
<td>3.5</td>
</tr>
</tbody>
</table>

**TAB. 3**

*Charge mix.*

*Composizione della carica.*

<table>
<thead>
<tr>
<th>Rebar Heats</th>
<th>Wire Heats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix HM 1 &amp; 2</td>
<td>P &amp; S</td>
</tr>
<tr>
<td>Shredded</td>
<td>Shredded</td>
</tr>
<tr>
<td>Turning + Skulls</td>
<td>Busheling</td>
</tr>
<tr>
<td>Cast Iron</td>
<td>Pig Iron</td>
</tr>
</tbody>
</table>

---

**FIG. 4**

*Modules’ Layout.*

*Disposizione dei moduli all’interno dell’EAF.*

**FIG. 5**

*Examples of scrap charged in Jacksonville EAF: shredded (on left) and cast iron (on right).*

*Esempi di rottame caricato nel forno di Jacksonville: shredded (a sinistra) e cast iron (a destra).*
This dense scrap allows charging all material with only one bucket reducing power off time and improving consumption and process conditions.

**Melting Procedure**

Figure 6 shows the detailed melting profile used in Jacksonville EAF.

**OPERATIONAL RESULTS**

**Consumptions**

The consumptions’ evaluation takes into account 200 consecutive heats. Among these, 7 sequences of at least 17 consecutive heats (the total number is 156) have been selected and their average production, process times and consumptions were calculated.

The average charged scrap weight is 94 t, whereas the tapped steel is equal to 87.3 t. The achieved yield is 93 % thanks to good scrap quality and foremost right process control, which allows reducing iron losses in the slag in terms of both iron oxide and embedded metal iron, reported in slag analysis.

The overall results are reported in Table 4.

The plant has actually a bottle neck at the existing caster and large EAF Tap to Tap time, the consequence is a long waiting due to caster’s low speed. A net tap to Tap time has been calculated which takes in consideration only the part due to EAF needs by neglecting the delay due to the caster which can be assessed to be around 10 – 11 min. In this way the net furnace productivity becomes 114 – 116 t/h which completely matches the requirements.

The achieved electric energy consumption is quite low, foremost by taking in consideration the tapping temperature of 1705 °C, around 80 °C greater than usual values of 1620 – 1630 °C (no LF available), and the caster’s delays. Any doubt regarding the reliability of the recorded tapping temperature can be elimi-

<table>
<thead>
<tr>
<th>Overall</th>
<th>Best</th>
<th>Data at 1630 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PROCESS TIMES</strong></td>
<td></td>
<td>(calculated from overall results)</td>
</tr>
<tr>
<td>Tap to Tap</td>
<td>56 min</td>
<td>54 min</td>
</tr>
<tr>
<td>Power on</td>
<td>35 min</td>
<td>34.5 min</td>
</tr>
<tr>
<td>Net Tap to Tap</td>
<td>45-46 min</td>
<td>43-44 min</td>
</tr>
<tr>
<td>Average Power</td>
<td>61 MW</td>
<td>61 MW</td>
</tr>
<tr>
<td><strong>TAPPING CONDITIONS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Content</td>
<td>0.17 %</td>
<td>0.15 %</td>
</tr>
<tr>
<td>Temperature</td>
<td>1705 °C</td>
<td>1703 °C</td>
</tr>
<tr>
<td><strong>ARRIVAL AT CASTER</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>1630 °C</td>
<td>1627 °C</td>
</tr>
<tr>
<td>Temperature Fall</td>
<td>75 °C</td>
<td>76 °C</td>
</tr>
<tr>
<td><strong>CONSUMPTIONS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric Energy</td>
<td>405 kWh/t</td>
<td>390 kWh/t</td>
</tr>
<tr>
<td>Oxygen</td>
<td>37 Nm³/t</td>
<td>36 Nm³/t</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>5.5 Nm³/t</td>
<td>5.5 Nm³/t</td>
</tr>
<tr>
<td>Injected Coal</td>
<td>14 kg/t</td>
<td>13 kg/t</td>
</tr>
<tr>
<td>Charged Lime</td>
<td>28.5 kg/t</td>
<td>25 kg/t</td>
</tr>
<tr>
<td>Injected Dololime</td>
<td>12 kg/t</td>
<td>13 kg/t</td>
</tr>
</tbody>
</table>

**FIG. 6** *Detailed melting profile.*

*Profili di fusione.*

**TAB. 4** *Achieved results (based on liquid steel weight).*

*Risultati ottenuti (rapportati alla massa di acciaio liquido).*
ted by analyzing the temperature fall at caster arrival. This value (75 °C) is certainly realistic and by taking in consideration that all ferroalloys are charged during tapping, it’s possible to state that it’s very low too. This result therefore confirms that the bath is uniformly heated up during the refining stage and that the measured temperature is representative for the whole tapped steel.

Table 4 shows also the best results achieved referred to a sequence of 10 consecutive heats. It’s worth pointing out that the achieved energy consumption is really excellent and could be considered a benchmark level for standard EAFs which tap steel at lower temperatures. In the last column of the potential results if the process would have been stopped at the temperature of 1630 °C are reported. A decrease of 2.9 minutes in power on time is achieved considering a superheating speed of 26 °C/MWh (see following paragraph), consequently electrical energy is reduced to 373 kWh/tls and the oxygen consumption lowers to 33 Nm3/tls.

Heating Rate

Measures of temperature rise during the refining stage have been collected in order to estimate the efficiency of the energy transfer from the arc to the steel in flat bath conditions which is strictly related to the foaming slag efficiency. Figure 7 shows the dependence of temperature on time and energy consumption. The slope of the two curves is respectively 26 °C/MWh and 26 °C/min. The value which is usually considered as specific heat of the steel during refining is 0.55 kWh/t. Starting from this value it is possible to estimate which should be the heating rate with the assumed arc thermal efficiency. By knowing that the average tapped steel weight is 87 t and considering a hot heal of 20 tons, the result is:

The ratio between the value obtained from the measures and this one is 1.53 (= 26 / 17), which means that the arc thermal yield in Jacksonville EAF is 53% greater than the usually supposed value. This result can be explained with excellent arc coverage due to a slag which foams easily and allows heat transfer from the arc to the bath thanks to the correct choice of oxygen, coal and lime flowrates.

Slag Samples

Slag samples were taken at the end of the heat and therefore the measured composition is related to the slag which was in the furnace just before tapping. The average slag composition is reported in the following Table 5 Tabella 5. The slag oxidation degree results very low because of a carbon content in the steel equal to 0.15% and the iron losses in the slag are limited to 15.8% (Figure 8 shows the variation of these value in dependence of steel carbon content based on empirical measures in various plants). This value certainly allows reaching high yields (93 % as reported in Par. 4.1) but at the same time proves the goodness of achieved electric consumption. In fact if it were possible to oxidize more iron increasing its percentage in the slag up to 22-23 %, the yield would slightly fall (92 %) whereas around 10 kWh/t of electric energy would be saved. The basicity indexes are the following:

\[
IB_2 = \frac{CaO}{SiO_2} = 1.7 \\
IB_3 = \frac{CaO}{[SiO_2+Al_2O_3]} = 1.2
\]

Slag’s viscosity is likely not to be very high because of high fluxing agents’ content (SiO₂, Al₂O₃, [FeO]n) and high tapping temperature. MgO, whose percentage is quite large, acts surely as viscofying agent even if greater contents would be needed in order to reach the proper viscosity value (at these conditions the saturation percentage of MgO is around 14-15%, see Figure 9).

<table>
<thead>
<tr>
<th>CaO</th>
<th>MgO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>MnO</th>
<th>Fe₂O₃</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.0%</td>
<td>11.8%</td>
<td>17.8%</td>
<td>7.7%</td>
<td>6.4%</td>
<td>22.5%</td>
<td>3.8%</td>
</tr>
</tbody>
</table>

FIG. 7 Temperature rise as function of energy consumption and time. 
Incrementi di temperatura in funzione del consumo di energia e del tempo.

FIG. 8 %Fe lost in slag (as FeO) in function of carbon content in steel.
Percentuale di Fe in scoria (come FeO) in funzione del contenuto di carbonio nell’acciaio.

FIG. 9 Isothermal solubility diagram.
Diagramma di solubilità isoterma.

TAB. 5 Average slag composition.
Composizione media della scoria.
The slag’s great efficiency in energy transfer from the arc to the bath must be a consequence of the proper regulation of carbon, oxygen and lime injection. A possible explanation is that the homogenous injectors’ distribution around the bath leads to uniform formation of CO bubbles which perform a good foaming of the whole slag layer. Moreover Hijet allows greater coal’s penetration into the slag layer leading to CO bubbles generation in depth in the slag: these ones together with bubbles derived from bath decarburisation spend more time inside the slag and therefore the foaming effect is likely to be more efficient.

Fumes
Fumes analysis has shown very interesting results too foremost regarding the post-combustion ratio. Figure 10 shows where outgoing fumes are sampled to be analyzed. It’s really worth watching the variation of CO and CO₂ percentage during the process. Figure 11 shows the data of a representative heat. The 0 value of the time scale refers to the start of measure and it’s not related to the process time. Electric energy, oxygen and gas profiles are reported as reference for fumes’ composition. The CO₂ is constantly greater than CO content during all process with post-combustion ratio values of 60 – 70% during burner phase and 80 – 90% during lance phase. This result means that high degrees of post-combustion are achieved inside the furnace, much greater than expected ones. This very good result is likely due to two main reasons:
• because of single bucket utilization, the scrap level in the first half of the heat is very high and even if post-combustion reaction happens near the EAF top, the released energy can be exchanged with the scrap.
• during the second half of the heat, the good foaming slag layer which is in contact with the steel increases the residence time of CO bubbles allowing the post-combustion reaction to happen inside the slag. In this way the released energy is transferred to the bath.

The oxygen which is necessary for post-combustion derives from:
• excess oxygen during burner phase thanks to O₂ to N.G. ratio greater than stoichiometric. The used excess flowrate is around 700 – 750 Nm³/h;
• shrouding utilization for Carbon and Lime jets and foremost from oxygen injected from Hijet annular nozzle during lance phase.

A further confirmation of the high amount of CO₂ in the fumes is the temperature measured after the settling chamber. In this point the expected value is around 800 °C whereas the measured one is close to 450 °C. The difference is likely due to the lack of CO in the fumes which would react with oxygen, which comes in with air entering from the gap between EAF elbow and FTP primary duct, giving CO₂ production and releasing energy.

PROCESS SIMULATION
Based on the collected data concerning: consumption, slag analysis, off gas analysis and thermal losses in the water-cooled panels of the EAF, the energy balance of the process was analyzed. In Figure 12, the sum of the energy inputs and of the energy outputs is reported.

The total energy input is given by:
• electrical energy, 405 kWh/tls,
• burner energy, 61 kWh/tls according to a natural gas consumption of 5.5 Nm³/tls,
• charge oxidation, 91 kWh/tls due to the oxidation of the elements present in the charge: C, Si, Mn and Fe in the amount allowed from the slag analysis,
• coal oxidation, 85 kWh/tls: in this term we considered the combustion of coal injected to CO, plus the partial post-combustion of CO, taking into consideration an average PCR inside the EAF equal to 72%.

The total energy output is given by:
• steel enthalpy, calculated according to the average tap temperature of 1705 °C,
• slag enthalpy, calculated according to the slag amount considered in the process, 103 kg/tls. This figure is confirmed from the slag builders addition, 40.5 kg/tls, and the slag composition, above reported,
• water losses were calculated from the average delta T measurements in the water-cooled panels of the roof and of the shell. The difference of temperature (output – input) from the start to the end of the process is varying from 1.5 to 7.2 °C, that in terms of thermal losses corresponds to 2 MW at the beginning of the process and 12 MW at the end of the process, see Figure 13.
• electrical losses: these are the losses due to joule effect with an average secondary current of 55 kA,
• dispersion from refractory, hot heel and remaining slag,
• off-gas losses. These losses are intended as sensible heat in the off gas. The data measured from the EAF off-gas is only the analysis, more specifically CO, CO₂, H₂O, O₂. No measure of temperature or flow-rate was taken in correspondence of the sampling probe location. Anyhow the percentage of CO and CO₂ measured allowed determining the degree of post-combustion occurred inside the EAF, and consequently the overall energy developed from the carbon combustion.

From this analysis we can state that the global energy yield, expressed as the ratio between the liquid steel enthalpy and the sum of the energy inputs of the process is equal to 63%. This value is higher than what experienced in other processes, that usually have the same overall consumption, but tapping at lower temperatures (1630 °C), and with tap carbon of approx. 0.06-0.08 %.

From the thermal and mass balance it results that among the overall oxygen consumption, 37 Nm³/tls, 8.2 Nm³/tls of oxygen are engaged in the combustion of CO inside the furnace. More specifically this means that 1 Nm³/tls derives from the excess of oxygen during the burner phase, while the remaining 7.2 Nm³/tls of oxygen are supplied during the lance phase. In other words 35 % of the oxygen supplied during the lance phase is engaged in post-combustion of CO.

The energetic benefit of this post-combustion oxygen is calculated to be 4.7 kWh/Nm³, which corresponds to a net input of 38.3 kWh/tls.

These results were achieved without having any detrimental effect on the process yield, which is maintained at high levels, 93%. From the slag analysis and the slag amount we can consider that the iron lost in the slag is limited to 16 kg/tls.

FUTURE DEVELOPMENTS
Some developments are foreseen for the furnace in the near future. First of all a second Limejet will be installed taking the place of Carbonjet 2 in order to perform all slagbuilders addition by injection limiting powder release and improving slag control.

Afterwards the installation of a LF and the caster revamping are likely to be done in the following years and consequently tapping temperature will be able to be decreased up to 1620 – 1630 °C improving EAF times (eliminating delays) and reducing consumption. By assuming the heating rate values reported in Par.4.2 (26 °C/min) the time saving is around 3 min whereas by using the same power during refining (60 MW) energy saving is around 30 kWh/t which means 375 kWh/t as overall consumption. The delays’ elimination would lead to a further reduction of energy consumption of around 17 – 19 kWh/t, being possible to assess that the furnace loses 1.73 kWh/t per minute of delay. Table 6 shows the expected improvements due to the future developments (productivity is calculated by assuming 10 min as average power off time and 87 t as tapped size).

<table>
<thead>
<tr>
<th>Power on</th>
<th>min</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>t/h</td>
<td>125</td>
</tr>
<tr>
<td>Electric Energy</td>
<td>kWh/t</td>
<td>355</td>
</tr>
</tbody>
</table>

TAB. 6 Expected future improvements.
Miglioramenti futuri previsti.
CONCLUSIONS
Jacksonville’s EAF process has demonstrated good thermal efficiency. This has been achieved exploiting the excellent quality of the material charged, its high degree of metallization, and the one bucket process.
These two preconditions allowed to combine in the best way the speed of the process, given by the electrical power applied, with the efficiency of the alternative energy applied that allowed to exploit in good extent the CO post-combustion. This result was obtained in the full respect of the tapping conditions requested by the absence of a ladle furnace, and without having detrimental effects on the process yield.
As described in the future improvements as soon as a ladle furnace is installed and the logistic delays are eliminated, a further increase in the EAF performance is expected.

Abstract

Processo Monocesta Fastarc™ a Jacksonville

Parole chiave: forno elettrico, acciaieria, efficienza termica, Fast Arc, singola cesta

Il presente lavoro descrive le caratteristiche principali del sistema AC Fastarc™ del forno elettrico Danieli installato nell’impianto Gerdau Ameristeel a Jacksonville (Florida - U.S.A.).
Il nuovo forno UHP Fastarc™ ne rappresenta lo stato dell’arte della tecnologia EAF. Esso ha una capacità stimata di 95 sht (≈ 86 t) ed è in grado di fondere una singola cesta con il 100% di rottame.
Grazie all’utilizzo esteso di energia chimica per mezzo del sistema di iniezione DANARC, e al dimensionamento ottimizzato del trasformatore (90 + 12% MVA), il forno ha raggiunto alte velocità di fusione della carica con scenari di risparmio energetico molto promettenti. L’EAF ha già raggiunto tempi di power on dell’ordine di 35 minuti con produttività massima di 115 t/h. Questo risultato è stato raggiunto grazie all’efficiente utilizzo dell’iniezione di ossigeno, carbone e calce, il quale ha permesso di garantire una buona schiumazione della scoria durante tutto il processo. L’analisi dei fumi ha rivelato un alto grado di post-combustione in forno, confermando un miglioramento anche sotto questo aspetto. Sono state dimostrate condizioni di omogeneità termica del bagno grazie a riduzioni della caduta di temperatura tra uscita dell’EAF e arrivo in colata continua (l’acciaieria non dispone di LF).
Il seguente lavoro presenta risultati molto interessanti dal punto di vista dei consumi e dell’efficienza termica, tenendo conto dell’analisi dei dati raccolti negli ultimi mesi di esercizio, del nuovo design concept e delle parti meccaniche ed elettriche installate.
The successful piloting of CRISP, the innovative continuous steelmaking technology

F. Wheeler, Y. Gordon, S. Broek, I. Cameron

Since inception, the Continuous Reduced Iron Steelmaking Process (CRISP), an innovative, patented technology for continuous steelmaking from pre-reduced iron ore, has undergone significant development. Most recently, pilot testing at the Swerea MEFOS AB in Luleå, Sweden successfully confirmed the viability of the underlying metallurgical principles as well as the practicality of continuous operation, setting the stage for the commercialization of this technology. The CRISP technology builds on existing practices and equipment, and thus represents a logical step in the ongoing development of electric steelmaking. The innovative use of a stationary electric furnace, common in other metals industries such as nickel or copper smelting, for continuous steelmaking is, however, a departure from the current trends and forms the basis of this new steelmaking technology. The unique features of the CRISP technology lead to important operational benefits. The paper will illustrate these benefits and the related capital and operating cost savings, and describe the current status and ongoing development of the CRISP technology.

The factors leading to a reduced environmental footprint are also outlined.

KEYWORDS: CRISP, Continuous steelmaking, stationary electric furnace, DRI-based steelmaking, slag control, steel decarburization, piloting steel technology

INTRODUCTION
Since the Continuous Reduced Iron Steelmaking Process (CRISP) was first presented in 2002 at the 7th European Electric Steelmaking Conference in Venice [1], this innovative patented technology pioneered by Hatch has undergone significant development. During this period the following was accomplished:
- Conceptual process parameters including slag engineering were developed;
- Preliminary design of the stationary electric furnace has been completed;
- Plant layouts including the critical interface with the DR furnace were prepared;
- Plant logistics were examined and computer-simulated;
- Preliminary capital and operating costs have been established;
- The economic viability of the technology was confirmed;
- A US and other patents covering the technology have been awarded [2].

Following this earlier conceptual development at Hatch [3, 4, and 5], fundamental research including laboratory tests was carried out at the Department of Materials Science and Engineering of the University of Toronto. This work confirmed the principles of the process and identified viable slag chemistries that would meet the demanding and often conflicting metallurgical requirements of the CRISP concept and set the stage for the next step: the pilot testing of the CRISP technology. The details of this slag engineering research and the analysis of the slag performance in the pilot trials have been described in an earlier paper [6].

Recent pilot testing at the research facilities of Swerea MEFOS in Luleå, Sweden successfully confirmed the viability of the underlying metallurgical principles as well as the practicality of continuous operation, setting the stage for the commercialization of this technology.

THE CRISP TECHNOLOGY
The CRISP process is not a radical departure from current steelmaking practices but rather a logical step in the ongoing evolution of steel technology from a batch process to continuous operations.

The essence of the CRISP process is the use of a large stationary refractory-lined electric furnace for the continuous melting of direct reduced iron (DRI). This type of furnace, shown schematically in Fig. 1, while novel to the steel industry, is well established in other metals industries and is found, for example, in nickel, copper, or ilmenite smelters.

In a CRISP plant, the charge material is fed continuously through the furnace roof from an overhead feed system. The feed rate is adjusted to maintain the target bath temperature. The furnace remains under power during electrode make-up and slipping, and tapping as well as during most refractory and tap hole repairs. The furnace is equipped with multiple tap holes for steel and slag. Steel is tapped periodically into ladles and processed in conventional downstream facilities: ladle metallurgical and continuous casting. Slag is tapped into slag pots and transported for processing in the yard.

PILOT TESTING OBJECTIVES AND TEST FACILITIES
The pilot testing was carried out in two separate campaigns on the 8-tonne AC electric arc furnace at Swerea MEFOS[7].
facility was selected, after an extensive world-wide search, in view of its staff of experienced researchers and technicians with internationally recognized expertise in the field of metallurgy and heavy pilot plant activities, as well as the well-equipped pilot plant facilities.

The Phase I trials in August 2007 were devoted to testing the interaction of slags of a selected composition with the steel bath, with the aim of identifying a window of appropriate operating parameters for the CRISP technology. A prime objective was to identify a slag composition that would provide the decarburization of the steel to below 0.10 %C and good foaming slag, while at the same time not erode the slag line refractories. In all, nine different slag compositions were tested on 14 heats over a period of four days. Varying levels of basicity and FeO contents were examined.

The Phase II trials in April 2008 then built on the positive results of the first round with the objective of demonstrating one of the key aspects of the CRISP process: the viability of continuous melting over an extended period. The target slag compositions identified in the Phase I trials, shown in Table 1, was used in the Phase II trials. The MgO content was maintained at 1 - 2% above saturation.

To facilitate the CRISP trials, Swerea MEFOS installed an overhead feed system, designed specifically to allow the controlled continuous feed of DRI along with oxide and flux materials. Batches of these materials were preweighed into hoppers which were then bottom-discharged into the overhead feed bin equipped with a weigh feeder.

The furnace operating parameters were selected to approximate the operations proposed for a CRISP furnace:

- The furnace power was set at 2 MW which equates to approximately 500 kW/m² of hearth area, the anticipated power density of the CRISP furnace;
- The target bath temperature of 1,600°C was maintained by adjusting the feed rate of materials (DRI / flux mixture).

For the Phase II continuous pilot trials, Swerea MEFOS fabricated four sandboxes to replace the steel ladles used in the Phase I trials.

![FIG. 1 Schematic of CRISP stationary electric furnace.](image)

**FIG. 1 Schematic of CRISP stationary electric furnace.**

**Schema del forno elettrico stazionario CRISP.**

![FIG. 2 Logistics of the Phase II trials.](image)

**FIG. 2 Logistics of the Phase II trials.**

**Logistica delle prove della Fase II.**

<table>
<thead>
<tr>
<th>Test #</th>
<th>Day</th>
<th>FeO wt%</th>
<th>B₄</th>
<th>C wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>As low as possible</td>
<td>2.0</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>As low as possible</td>
<td>2.0</td>
<td>0.04 and 0.06</td>
</tr>
</tbody>
</table>

**TAB. 1 Target starting slag compositions; Phase II (continuous) pilot trials.**

Prescrizioni di composizione iniziale delle scorie, prove con impianto pilota Fase II.
I trials. This eliminated the need to superheat the steel prior to tapping and enabled the near-continuous mode of operation. The logistics of the Phase II pilot trials are shown schematically in Fig. 2. The 8-tonne furnace is shown in Fig. 3.

PILOT TEST RESULTS AND DISCUSSION
In the Phase I trials a total of 14 heats were made in a four-day period with an overall consumption of 70 tonnes of DRI. The longest trial, consisting of five continuous heats, lasted approximately twelve hours. The key findings from the Phase I pilot trials were:

- It is possible to produce low-carbon steel (below 0.10 wt% C) with a good foaming slag and low FeO (below 18 – 20 wt%);
- The relationship between FeO and C is closer to equilibrium than that experienced in conventional EAF steelmaking (Fig. 4);
- This can be achieved without the use of gaseous oxygen;
- No major refractory erosion was experienced under these conditions;
- Stable and reproducible operating conditions can be achieved;

These findings allowed a window of operating parameters to be defined that would enable sustained and reproducible continuous steelmaking using the CRISP technology. They served as the basis for the Phase II pilot trials.

The total campaign time of the Phase II pilot trials carried out in April 2008 was 115 hours, in which time 254 tonnes of DRI were melted to make 52 'heats' in a continuous mode. As seen from Fig. 5, the trial heats were carried out in four distinct phases (1-4). The bath temperature was maintained close to the target 1,600 °C throughout the trial heats (Fig. 6) while the slag FeO content varied according to the target bath carbon in the trial phase.

- In Phase 1 the objective was to establish the steady state melt in carbon without the addition of iron oxides (mill scale or iron ore). This was reached in approximately 14 hours when the carbon plateaued at 0.5 – 0.6 wt% C, close to the stoichiometric value calculated from the carbon and residual oxide content in the DRI. At this point, gradual additions of mill scale were made with the intent of bringing the bath carbon down to 0.10 wt% C, the target level set for Phase 2.
can be produced on a CRISP furnace. The bath has a positive impact on the range of steel qualities with continuous feed of DRI. This lower nitrogen content of the steel usually results in significantly higher nitrogen levels, even below 40 ppm, and often less than 20 ppm. This is very low for pilot trials showing an excellent refractory endurance. These encouraging results can be attributed primarily to the properties of the slag: good foaming action with low FeO levels and MgO saturation.

One of the most important findings of the trials was the confirmation that the process conditions of the CRISP technology allow the bath carbon to be controlled in a consistent and repeatable manner, solely by adjusting the slag FeO and without the use of gaseous oxygen. Another factor important for the economic viability of the CRISP technology is the ability to sustain the furnace refractories over an extended period without erosion. As seen from the measurements of the furnace refractory profiles made before and after the trials (Fig. 7), after two campaigns lasting in total approximately 200 hours of operation and without refractory repairs, there is, with the exception of minor erosion opposite the hot (B) phase, no loss of refractory. In fact, there is actually a net deposit of 66 mm. This was accomplished on an electric arc furnace without water-cooled sidewall panels or roof.

This is regarded as one of the most promising outcomes of the pilot trials showing an excellent refractory endurance. These encouraging results can be attributed primarily to the properties of the slag: good foaming action with low FeO levels and MgO saturation.

The nitrogen content found in the steel was another important finding in the pilot trials. The dissolved nitrogen was consistently below 40 ppm, and often less than 20 ppm. This is very low for an EAF steelmaking process where arcing together with air ingress usually results in significantly higher nitrogen levels, even with continuous feed of DRI. This lower nitrogen content of the bath has a positive impact on the range of steel qualities that can be produced on a CRISP furnace.

FIG. 7 Furnace refractory profile before and after Phase I and Phase II trials. Profilo del refrattario del forno prima e dopo le prove della Fase I e II.

• In Phase 2 the carbon level was held in the vicinity of the targeted value for 33 hours of continuous operation, after which time it was decided to reduce the bath carbon to 0.04 wt% C.
• The Phase 3 carbon level was reached after a transition period of three hours and held for 38 hours of continuous operation.
• For Phase 4, the final phase of the trials, the target carbon level was set between that of Phase 2 and 3, at 0.06 wt% C.

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**BENEFITS OF THE CRISP TECHNOLOGY**

The dramatic development of EAF steelmaking technology in recent decades has been well documented. Ever-increasing furnace power levels together with the introduction of large amounts of chemical energy and innovative practices, such as the foamy slag practice and eccentric bottom tapping, have lead to unprecedented advances in EAF productivity. Not only are heats churned out in tap-to-tap times routinely under one hour; power and electrode consumption have dropped to a fraction of previous levels.

These trends are not, however, without their limitations, and ongoing innovation requires a fresh approach rather than incremental improvements. CRISP represents such a departure from the current trends. This is illustrated in Table 2, in which the key differences of a CRISP furnace as compared to a conventional steelmaking electric arc furnace (EAF) are highlighted, using a nominal 1.5 million t/yr plant as an example.

The essence of the unique features of the CRISP technology is:

- Continuous melting without downtime for charging, tapping or tapping;
- Large liquid heel with the attendant long residence of metal in the furnace;
- Power density in the range of 300 to 500 kW/m² of hearth, a fraction of the level on a conventional EAF, typically 2,500 kW/m² to 3,000 kW/m²;
- The ability to decarburize to low levels of carbon (> 0.04 wt% C) without the use of gaseous oxygen.

These differences lead to significant operational benefits, the most important being:

- Decarburization is accomplished at slag FeO levels closer to equilibrium;
- The related improved yield provides meaningful savings in the cost of metallics;
- Furnace refractory life is measured in years rather than weeks or months;
- The high furnace availability, approaching 8,000 hours/year, leads to improved plant logistics (matching) with upstream and downstream facilities;
- The shielding of the arcs is accomplished by utilizing the foaming slag inherent to the continuous melting of DRI;
- The low gas velocity in the furnace freeboard significantly reduces the amount of dust carried over from the furnace. This not only reduces the dust disposal costs but also allows the charging of fine materials to the furnace, a cost-effective measure;
- The specific energy requirement – power, oxygen, natural gas and carbon – is lower than on a conventional EAF; in the comparison case: 610 kWh/tonne liquid steel versus 756 kWh/tonne liquid steel;
- The continuous nature of the CRISP operation together with the furnace design allows the furnace off gas to be captured and utilized as a fuel gas;
- The steady even furnace power load of the continuous CRISP operation reduces the demands on the electrical utility grid. It also enhances the feasibility of connecting to a captive power plant;
- The GHG (green house gas) footprint and especially the NOx emissions are significantly lower.

These benefits translate into an operating cost advantage of the CRISP process as compared to conventional EAF steelmaking in terms of cost per tonne of liquid steel. The savings stem primarily from lower overall energy costs and improved yields, as well as lower costs for refractory, oxygen and electrodes. These are quantified in Section 6.

It was also found that about 85% phosphorus reported to slag. This improvement in de-phosphorization capability of the steel-
making process is mainly attributed to the lower process temperature. Additional theoretical and experimental study will be required to better understand the mechanism of phosphorus partition between steel and slag in the CRISP furnace environment.

REDUCED ENVIRONMENTAL FOOTPRINT

The features of the CRISP process described above translate into a meaningful reduction in the environmental footprint. The specific areas impacted are discussed below:

**NOₓ.**

Since the CRISP furnace has minimal air ingress, the NOₓ concentrations are well below 50 ppm. This is in contrast to a conventional EAF, where the large ingress of air combined with the arc action lead to much higher NOₓ concentrations. Measurements made during the pilot trials at MEFOS support these projections. During the MEFOS trials, an average of 47 g/t and a maximum of 118 g/t were recorded, with the higher numbers being experienced when the slag door was opened. The emissions expected from a CRISP demonstration furnace are even lower, as the furnace will be operated under positive pressure, with no post combustion of the gas in the fume duct and no furnace doors opened during operation. By contrast, in conventional EAF operations, typically 200 g/t NOₓ is generated.

**Dust.**

The low gas velocity in the furnace freeboard significantly reduces the amount of dust carried over from the furnace. This not only reduces the dust disposal costs but also allows the charging of fine materials to the furnace, a cost-effective measure.

**GHG gases.**

The GHG related to the steelmaking and ladle metallurgy operations of a CRISP plant are approximately 25% lower than those of an EAF plant, despite the higher electrical power consumption projected for the CRISP operations (Fig. 8). This is primarily due to the reuse of the off gas of the CRISP furnace as well as the fact that carbon materials and oxygen are not used as auxiliary energy in the CRISP furnace. This represents a distinct environmental advantage of the CRISP technology.

**ONGOING DEVELOPMENT**

The two campaigns of pilot testing at Swerea MEFOS were critical to the development of the CRISP technology. The test results validated the underlying metallurgical concepts, thus allowing the process design to be advanced. Some of the specific areas involved were:

- slag design and process control strategy;
- calculation of material and energy requirements;
- stationary furnace design;
- refinement of plant layouts;
- definition of auxiliary equipment;
- assessment of plant logistics;
- update of operating and capital costs.

This information was incorporated into a comparative feasibility study aimed at benchmarking the CRISP technology with the current EAF technology. A CSP plant producing 1.5 million tonnes/year of hot band was selected as a type of plant that would lend itself to a readily recognizable ‘apples-to-apples’ comparison. The main process facilities of the plant are:

- Direct reduction plant;
- Electric arc furnace (Stationary electric furnace);
- Ladle metallurgy furnace;
- Thin slab caster;
- Tunnel furnace;
- Compact hot strip mill.

---

**TAB. 2** Key operating parameters of a CRISP furnace as compared with a conventional EAF for a 1.5 million tonne/year plant.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hot DRI Charged EAF</th>
<th>CRISP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Operating Time (hours/year)</td>
<td>7,200</td>
<td>8,000</td>
</tr>
<tr>
<td>Power-on Time / Occupancy (hours/year)</td>
<td>5,414</td>
<td>7,440</td>
</tr>
<tr>
<td>Production rate (tonnes liq steel/hour)</td>
<td>285</td>
<td>207</td>
</tr>
<tr>
<td>Hearth area (m²)</td>
<td>38</td>
<td>329</td>
</tr>
<tr>
<td>Heat size (tonnes)</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Hot heel (tonnes) (average)</td>
<td>50</td>
<td>1,000 to 1,500 (1,317)</td>
</tr>
<tr>
<td>Approximate residence time (hours)</td>
<td>0.75</td>
<td>7.15</td>
</tr>
<tr>
<td>Total energy consumption (ekWh/tonne)</td>
<td>756</td>
<td>610</td>
</tr>
<tr>
<td>Electrical power consumption (kWh/tonne liq steel)</td>
<td>428</td>
<td>510</td>
</tr>
<tr>
<td>Electrical power average/peak (MW)</td>
<td>113/137</td>
<td>106/127</td>
</tr>
<tr>
<td>Power density (kW/m²)</td>
<td>3,840</td>
<td>385</td>
</tr>
</tbody>
</table>

**FIG. 8** Comparison of GHG emissions from steelmaking and ladle metallurgy operations of an EAF and CRISP plant.

Confronto fra le emissioni GHG da operazioni siderurgiche e di riviera di un impianto EAF e CRISP.
Electric Furnace

<table>
<thead>
<tr>
<th>MATERIALS</th>
<th>Units $US/unit</th>
<th>Units/t LS $US/t</th>
<th>Units $US/unit</th>
<th>Units/t LS $US/t</th>
<th>$US/t LS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRI</td>
<td>242.8</td>
<td>1.15</td>
<td>278.39</td>
<td>1.08</td>
<td>262.21</td>
</tr>
<tr>
<td>Mill Scale</td>
<td>-</td>
<td>0.01</td>
<td>-</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Pellets (mill scale subsidy)</td>
<td>121.00</td>
<td>0.03</td>
<td>3.29</td>
<td>0.03</td>
<td>3.29</td>
</tr>
<tr>
<td>Total burnt lime</td>
<td>113.61</td>
<td>0.032</td>
<td>4.18</td>
<td>0.035</td>
<td>3.96</td>
</tr>
<tr>
<td>Burnt dolomite</td>
<td>133.00</td>
<td>0.01</td>
<td>1.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtotal materials</td>
<td></td>
<td></td>
<td>287.39</td>
<td></td>
<td>271.67</td>
</tr>
</tbody>
</table>

CONVERSION COST

<table>
<thead>
<tr>
<th>Item</th>
<th>$/ hr</th>
<th>$/hr</th>
<th>$/ hr</th>
<th>$/hr</th>
<th>$/hr</th>
<th>$/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour</td>
<td>45.00</td>
<td>0.11</td>
<td>4.95</td>
<td>0.11</td>
<td>4.95</td>
<td></td>
</tr>
<tr>
<td>Repairs and maintenance</td>
<td>6.00</td>
<td></td>
<td>3.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refractory</td>
<td>3.00</td>
<td></td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total electricity</td>
<td>0.06</td>
<td>428</td>
<td>25.68</td>
<td>510</td>
<td>30.60</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.10</td>
<td>32.00</td>
<td>3.04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRISP gas production</td>
<td>0.00</td>
<td></td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft / demin. water</td>
<td>0.22</td>
<td>0.01</td>
<td>0.001</td>
<td></td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Cold water</td>
<td></td>
<td></td>
<td>0.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>5.00</td>
<td>0.11</td>
<td>0.54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphite electrodes (EAF)</td>
<td>4,233.00</td>
<td>0.002</td>
<td>6.77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soderberg electrodes (CRISP)</td>
<td>640.00</td>
<td>0.002</td>
<td></td>
<td>1.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contingency, 10%</td>
<td>5.00</td>
<td></td>
<td>4.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtotal conversion cost</td>
<td>54.98</td>
<td></td>
<td>44.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total electric furnace costs</td>
<td>342.37</td>
<td></td>
<td>316.58</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LADLE METALLURGY

Conversion Cost 1

<table>
<thead>
<tr>
<th>Item</th>
<th>EAF</th>
<th>CRISP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material handling / stockyard</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>Ironmaking (DRI unit)</td>
<td>398</td>
<td>398</td>
</tr>
<tr>
<td>Steelmaking (Electric furnace)</td>
<td>208</td>
<td>200</td>
</tr>
<tr>
<td>Steel refining (LMF)*</td>
<td>23</td>
<td>38</td>
</tr>
<tr>
<td>Steel finishing (CSP)</td>
<td>463</td>
<td>463</td>
</tr>
<tr>
<td>Utilities and auxiliaries</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Infrastructure &amp; civil works</td>
<td>78</td>
<td>78</td>
</tr>
<tr>
<td>Administration facilities</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Sub-total</td>
<td>1,274</td>
<td>1,282</td>
</tr>
<tr>
<td>EPCM</td>
<td>76</td>
<td>77</td>
</tr>
<tr>
<td>Contingency</td>
<td>203</td>
<td>204</td>
</tr>
<tr>
<td>Total project costs</td>
<td>1,553</td>
<td>1,562</td>
</tr>
</tbody>
</table>

* Note that the CRISP LMF capital cost estimate is larger than the EAF due to the need for two twin-position LMFs in the CRISP process route.

1) The LMF conversion cost is marginally more expensive for the CRISP process route since the liquid steel will require more time (and hence use more electricity) in the LMF due to its lower tapping temperature.
In the study it was assumed that the metallic charge is 100% DRI; 90% hot/10% cold. A comparison of the furnace parameters is found in Table 2 above.
The operating and capital costs developed in the comparative feasibility study are shown in Table 3 and Table 4 respectively. While the capital costs of the plant are essentially identical, the estimated operating costs show a meaningful advantage of the CRISP plant – approximately $25/tonne. This, together with the operating advantages described above make a compelling case to consider the CRISP technology.
The comparative feasibility study is an essential summary benchmark document and an integral part of the ongoing commercialization program.

Acknowledgement

The development of the CRISP technology has been funded, in part, by Natural Resources Canada CANMET and the Ontario Center of Excellence. The authors wish to thank both agencies for their continuing support.

REFERENCES
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Abstract

L'impianto pilota del processo CRISP, tecnologia innovativa per la fabbricazione dell'acciaio in continuo

Parole chiave: impianti e processi, siderurgia

Il processo CRISP (Continuous Reduced Iron Steelmaking Process), una tecnologia innovativa brevettata per la produzione dell'acciaio in continuo da pre-riduzione del minerale di ferro, ha subito uno sviluppo significativo rispetto allo stadio iniziale. Recentemente, le prove pilota effettuate presso il MEFOS AB di Luleå, Svezia, hanno confermato in modo soddisfacente la validità dei principi metallurgici di base, nonché la praticabilità del funzionamento in continuo, creando quindi le condizioni per la commercializzazione di questa tecnologia.

Il processo CRISP si basa su pratiche e attrezzature esistenti, e rappresenta quindi un passo logico nello sviluppo dell' acciaieria elettrica. L'uso innovativo di un forno elettrico stazionario - comune in altre industrie dei metalli come per la fusione di nichel o di rame -, rispetto alle attuali tendenze nella produzione dell'acciaio in continuo, rappresenta tuttavia una svolta e costituisce la base di questa nuova tecnologia di fabbricazione dell'acciaio.

Le caratteristiche uniche della tecnologia CRISP sono in grado di portare notevoli vantaggi operativi. Il documento illustra tali vantaggi e i relativi risparmi di capitale e costi operativi, e descrive lo stato attuale e gli sviluppi in corso della tecnologia CRISP.

Vengono anche riportati i fattori che determinano una riduzione dell'impatto ambientale.
La tecnologia del forno intelligente (iEAF®): concetti di base, descrizione generale e dettagli della prima installazione

P. Clerici, V. Scipolo, P. Galbiati, E. Malfa, V. Volponi

L'iEAF® di Tenova è un innovativo sistema di automazione per il controllo dinamico e l’ottimizzazione olistica del forno elettrico ad arco. I modelli matematici del processo vengono utilizzati, unitamente alla composizione chimica dei fumi (acquisita tramite il sistema di analisi proprietario EFSOP®), ed insieme anche ad altre informazioni relative allo stato del processo ottenute tramite sensori innovativi sviluppati appositamente per l’applicazione sull’EAF, al fine di calcolare i bilanci di massa ed energia in modo dinamico ed in tempo reale. L’insieme dei modelli e dei sensori permette all’operatore di disporsi di informazioni critiche per la produzione quali l’energia netta fornita alla carica metallica, la percentuale di fusione del rottame, la temperatura e composizione del bagno e della scoria.

PAROLE CHIAVE: analisi dei fumi, bilancio di massa ed energia, produzione acciaio all’EAF, decarburazione, acciaieria, modellazione, controllo processi, energia
sigono e combustibili, l’energia elettrica e la portata, temperatura e composizione degli off-gas. Su tale base vengono calcolati i bilanci di massa che permettono a loro volta di ricavare in modo dinamico l’ossidazione e la decarbonizzazione.

Un’altra parte del modello si occupa del bilancio di energia che permette di calcolare le perdite nette di energia dai gas. L’energia netta viene poi ripartita tra perdite al forno ed energia fornita per riscaldare/ondere la parte solida (rottame, DRI, aggiunte, etc.) ed il bagno/scoria.

Il “Melting model” dell’iEAF® è stato sviluppato in collaborazione con il CSM sulla base degli algoritmi dell’iCSMelt® (8). Partendo dall’energia netta (sia chimica che elettrica) il modello calcola la distribuzione dell’energia tra riscaldamento (aumento della temperatura della carica) e fusione (dal solido al liquido). In tale modo si calcola il grado di fusione e ciò permette di “sincronizzare” la colata non solo sulla base del consumo di energia (kWh/ton).

Il “Dynamic Bath/Slag model” dell’iEAF® è basato sul software dyCoSMelt® (9) del CSM che descrive le condizioni bagno/scoria per il convertitore BOF, adattato per l’uso nell’EAF. Questo modello valuta in real-time lo stato del bagno e della scoria (temperatura e composizione).

La diversità di base tra l’approccio di Tenova e quello di altri sta nel fatto che la composizione degli off-gas non è un parametro stimato ma è un valore rilevato dall’impianto in modo continuo ed affidabile e ciò permette di calcolare un bilancio che veramente tiene in conto la variabilità del processo all’EAF durante la colata e tra una colata e l’altra.

La sincronizzazione dell’EAF
Normalmente l’apporto di energia chimica al forno è regolato sulla base di profili che definiscono i set points in funzione dell’energia specifica (kWh/t). Ciò significa che il funzionamento del forno è temporizzato/sincronizzato sulla base dell’“orologio” dell’energia specifica.

Ciò però non sempre corrisponde al reale avanzamento del processo che invece deve garantire una progressiva fusione della carica. Il principio dell’iEAF® e dei suoi modelli è quello di modificare i set-points chimici ed elettrici sulla base dell’avanzamento della fusione (melting percentage).

Moduli di Controllo, Ottimizzazione e Sicurezza
L’iEAF® comprende i moduli di controllo ed ottimizzazione che realizzano le azioni sull’impianto in funzione dei valori di processo misurati e/o calcolati dai modelli. Tra questi moduli quelli più significativi sono:
• Il modulo di rilevazione presenza acqua in forno;
• Il modulo di ottimizzazione della post-combustione (su base di minor costo);
• L’ottimizzatore dell’energia elettrica;
• Il modulo di riconoscimento dell’inizio di affinazione;
• Il modulo per l’ottimizzazione della scoria schiumosa;
• Il modulo di “End-point detection”.

RISULTATI PRELIMINARI DELLA PRIMA APPLICAZIONE DELL’iEAF® IN TENARIS DALMINE

TenarisDalmine, stabilimento di Dalmine (BG) Italy, ha accettato di collaborare alla installazione e prova della prima applicazione della tecnologia iEAF® di Tenova. Un esempio delle pagine SCADA realizzate per TenarisDalmine, è riportato in Figura 1. I modelli di processo di iEAF® sono installati e funzionanti. La Figura 2 riporta la tipica composizione degli off-gas di una colata. Durante la fase di fusione si nota una concentrazione di acqua compresa tra 15%-30%; durante l’affinazione invece si aggira attorno al 5%. Gli elevati valori riscontrati in fusione sono legati alla evaporazione dell’acqua che entra con il rotame, a quella di raffreddamento elettrodi ed alla combustione degli idrocarburi.
Il bilancio di idrogeno e nitrogeno rende possibile il calcolo della portata di aria e acqua che entra come mostrato in Figura 3. La Fig. 4 mostra, per una colata tipica, le percentuali di ossidazione e decarbonizzazione con l’evoluzione del contenuto di FeO + MnO nella scoria. Si vede in modo chiaro come l’ossidazione della carica sia influenzata dalle condizioni del processo (l’ossidazione della seconda cesta e l’influenza del carbone iniettato). Questo dimostra come l’iEAF® possa sfruttare le misure degli offgas per valutare importanti parametri di processo come ossidazione e decarbonizzazione.

Anche la composizione della scoria viene calcolata durante la colata come mostrato in Fig. 5. Il sistema calcola anche l’indice di basicità IB2; in futuro questo dato, insieme con il “Isothermal Stability Diagrams (ISD)”, permetterà di mostrare la schiumosità della scoria ed in tale modo prendere decisioni sul controllo dell’iniezione di carbone e calce per ottenere la formazione ottimale della scoria schiumosa.

Il modello bagno/scoria dell’iEAF® permette di calcolare in tempo reale la temperatura ed il carbonio del bagno come mostrato in Fig. 6. Questo calcolo è la base per realizzare l’“end-point optimizer”.

I modelli dell’iEAF® calcolano in modo dinamico il bilancio di energia. La Figura 7 mostra la potenza disponibile per scaldare e fondere rispetto a quella puramente elettrica. L’energia disponibile è quella totale fornita(elettrica più chimica) meno le perdite attraverso i pannelli raffreddati e gli offgas. Come
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In generale la migliore conoscenza del processo di produzione dell’acciaio all’EAF contribuirà ad un più efficiente funzionamento ed allo studio di nuove strategie di ottimizzazione. Lu- minari e pionieri della termodinamica come William Thoms- on, Lord Kelvin (1824-1907), hanno detto: “Quando tu puoi misurare ciò di cui stai parlando, esprimendolo in numeri, tu sai qualcosa; ma quando non sei in grado di misurarlo e non sei in grado di esprimerlo in numeri, allora la tua conoscenza è scarsa ed insoddisfacente …..” L’iEAF® è stato pensato e progettato per descrivere il processo all’EAF il più possibile in modo quantitativo e con ciò portare ad un controllo il più possibile efficiente.

FIG. 8 Confronto tra le temperature di spillaggio calcolata e misurata (in gradi Celsius) per una sequenza di 9 colate consecutive.

A comparison of the calculated and measured tap temperatures (in degrees Celsius) for a string of 9 consecutive heats.

Evidenziato, durante la fusione della prima cesta, la potenza disponibile supera quella elettrica di circa 5 MW, dimostrando i benefici della post-combustione. Al contrario durante l’affinazione la potenza disponibile è inferiore a quella elettrica per circa 10 MW per poi aumentare sino ad essere uguale al tempo 1700 secondi. Da quel punto decresce. Ciò indica la possibilità di ottimizzazione tramite riduzione delle perdite.

La Figura 8 mostra il confronto tra le temperature di spillaggio calcolate dall’iEAF® e quelle reali misurate per 9 colate consecutive. Si nota che in un solo caso la differenza tra le temperature stimata e quella reale è superiore a 20 gradi Celsius.

Benefici attesi e sviluppi futuri

L’iEAF®, una volta completata la messa a punto definitiva, sarà in grado di portare benefici importanti in aggiunta a quelli già verificati e legati alla grande quantità di informazioni aggiun- tive, fornite dai modelli. Durante la fusione la migliore gestione e controllo della chimica garantisce:

- La riduzione del tempo di power-on.
- La riduzione dei ritardi dovuti al caricamento anticipato della carica.
- La riduzione delle perdite dovute al ritardo di caricamento della carica.
- L’ottimizzazione dell’utilizzo di ossigeno, combustibile ed energia elettrica.
- Un più efficiente controllo dell’impianto fumi bilanciato tra le prestationi del forno e la riduzione degli scarichi.

- Aumento della sicurezza in acciaieria.

I moduli di controllo avanzato della fase di affinazione (Refining Start, Foamy Slag Optimizer, End-Point Optimizer) permettono di:

- Evitare la sovraossidazione del bagno ed in tale modo minimizzare le perdite di resa metallica e l’uso di costosi de-ossidanti.
- Bilanciare la pratica della scoria schiumosa ottenendo una riduzione del consumo di refrattario, una diminuzione delle perdite di energia ed un miglioramento della resa grazie alle perdite in scoria.
- Ridurre la variabilità dell’end-point genera un miglioramento dei flussi e della logistica globale dell’acciaieria ed un minor numero di campioni di temperature e carbonio prima dello spillaggio.

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Abstract

The intelligent furnace technology (iEAF®):
conceptual design, technical overview and details about the first installation

KEYWORDS: off-gas analysis, mass and energy balances, process control, EAF steelmaking

Tenova’s iEAF® is an innovative automation system for the dynamic control and holistic optimization of the electric arc furnace. Mathematical process models are used, along with real-time off-gas composition (EFSOP™ off-gas analysis system), and other process information provided by novel sensors developed for the EAF, to calculate dynamically mass and energy balances of the furnace in real-time. These models and sensors provide the operator with crucial steel-making information such as the net energy to the metallic charge, scrap melting percent and bath and slag composition and temperature. The increased process knowledge provided by the iEAF® makes it possible to take a holistic approach to furnace optimization and control that can be tailored to the operational objectives of the meltshop (e.g. increased productivity, improved economical performance through reduced conversion costs, reduced process variability, environmental and/or safety). This paper outlines the main components and features of this innovative technology including results from its premier implementation at TenarisDalmine.

The iEAF® dynamic process models have been implemented at TenarisDalmine and efforts are being made towards tuning and validation. The iEAF® control modules have also been developed and installed. Once fully implemented, the iEAF® will provide a variety of benefits to the steel-maker over and above the already significant advantages provided by the increased amount of information provided by the models.

During the melting phase, the pacing and control of the chemical package will ensure:
• A reduction in power-on-time.
• A reduction in delays attributed charging the furnace too early.
• A reduction in energy losses attributed to charging the furnace too late.
• Optimization of oxygen, fuel and electrical energy usage.
• Efficient fume system control that is balanced against furnace performance and melt-shop air quality.
• Safety in the melt shop through the early detection of water in the freeboard.

The advanced control modules for refining (Refining Start, Foamy Slag Optimizer, End-Point Optimizer) will ensure:
• Avoiding over-oxidation of the bath and thereby minimizing yield losses and the use of expensive de-oxidants.
• Balancing the foamy slag practice and thereby decreasing refractory wear, decreasing energy losses during refining and increasing yield through slag losses.
• Reduction in the number of samples of temperature and carbon required to conclude a heat.

The deeper understanding of the EAF steelmaking process and operation provided by the iEAF® will no doubt contribute greatly towards more efficient operation and to the development of future optimization strategies for the EAF. Scientist and pioneer in thermodynamics, William Thomson, Lord Kelvin (1824-1907), has been quoted as having said: “When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge of it is of a meager and unsatisfactory kind...” It follows that one cannot possibly control what one cannot measure. The iEAF® has been designed to explain the EAF process as quantitatively as possible by using real-time measurements of furnace off-gas composition and other measurable process parameters. It builds upon this information through process models that quantify the EAF process dynamically and in real-time. Quantification of the process enables precise control of the melting and refining phases of the operation; first of all through pacing of the furnace according to the total energy (not only electrical) delivered to the scrap and steel, and secondly through optimization modules that have been designed to control the furnace in the most efficient manner possible.